UNIVERZA V LJUBLJANI

Faculty of Mechanical Engineering

Design of a Bending Beam for manufacturing with Additive Technologies

Konstruiranje upogibnega nosilca za izdelavo z dodajnimi tehnologijami

A Master's thesis of the second-cycle master's study programme in MECHANICAL ENGINEERING – a research and development programme.

Pau Mendieta Pons

Ljubljana, February 2019

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Mentor: Prof. phD. Jernej Klemenc, univ. dipl. inž.

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Finally, I would like to thank Fakulteta za strojništvo, University of Ljubljana, and my home university, ETSEIB-UPC, for making this thesis exchange, Erasmus+, possible.

Declaration

I, the undersigned Pau Mendieta Pons, student from Erasmus+ Exchange on the Faculty of Mechanical Engineering at the University of Ljubljana, with registration number 70081778, author of the written final work of studies, entitled: **Design of a bending beam for manufacturing with additive technologies**,

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Izvleček

UDK 624.072.2:621.9.04(043.2)

Tek. štev.: MAG II/629 E

Konstruiranje upogibnega nosilca za izdelavo z dodajnimi tehnologijami

Pau Mendieta Pons

Ključne besede: dodajne tehnologije
upogibni nosilec
votli nosilec
modeliranje z odlaganjem filamenta
prototipiranje z dodajnimi tehnologijam.

Prototipiranje je draga faza v procesu razvoja izdelka. Pogosto se za izdelavo prototipov uporablja enaka ali podobna tehnologija kot za serijske proizvode, zato so prototipi lahko zelo draga. V prihodnosti lahko dodajne tehnologije znatno pocenijo izdelavo prototipov ali malo-serijskih izdelkov.

V tej magistrski nalogi smo se ukvarjali z mejami izbrane dodajne tehnologije za izdelavo pol-votlih izdelkov. Z uporabo različnih dodajnih tehnologij in njihovih omejitev je namreč mogoče izdelovati različno votle izdelke brez dodatnih nepotrebnih podpornih struktur. To pa seveda vpliva na konstruiranje izdelkov s ciljem njihove izdelave z dodajnimi tehnologijami.

V nalogi prikazana metodologija je bila preskušena na izdelavi pol-votlih nosilcev s ciljnim odlaganjem filamenta. Uporabljen je bil termoplast PLA. Upogibni nosilci z različnimi prerezi so bili uspešno izdelani z izbrano dodajno tehnologijo in nato tudi preskušeni. Ponovljivost izdelave in rezultatov preskusov je bila dobra. V bodoče bi lahko prikazano metodo razširili tudi na dodajno tehnologijo združevanja v prašni kopeli.

Abstract

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Design of a bending beam for manufacturing with additive technologies

Pau Mendieta Pons

Key words: Additive Manufacturing
Bending Beam
Hollow Beam
Fused Deposition Modelling
Additive Manufacturing Prototyping

Prototyping or materialisation is an expensive stage of Product Design. In a lot of cases, the same technology is both used for the final product and test models; this makes the prototype units very expensive. The use of Additive Manufacturing to build prototypes and small lot parts might be incredibly useful in the future, reducing costs drastically.

In this thesis, the limitations of Additive Manufacturing are faced creating a method that allows the production of semi-hollow parts. Depending on the AM Technology used and its own limitations, different geometries and parameters may change, allowing the part to be more or less hollow. However, the AM method designed may be the same.

The current method has been tested using Fused Deposition Modelling Technology using PLA thermoplastic. The bending beams were successfully printed and tested, giving good results and repeatability. Moreover, having determined that it works on FDM, the same method could be used for Powder Bed Fusion Technology and other AM Technologies.

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List of symbols used

Symbol	Unit	Meaning
A	mm^2	surface area
I	mm^4	moment of inertia
b	mm	width of the beam
h	mm	height of the beam
t	mm	thickness of the beam

Indices

List of acronyms used

Acronym	Meaning
AM	Additive Manufacturing
FDM	Fused Deposition Modelling
FE	Finite Element
PBF	Powder Bed Fusion
TM	Traditional Manufacturing

1 Introduction

1.1 Background

Prototyping or materialisation is an expensive stage of Product Design. In a lot of cases, the same technology is both used for the final product and test models; which makes the prototype units very expensive.
The use of Additive Manufacturing (AM) to build prototypes might be incredibly useful in the future, reducing drastically the prototypes costs. On the other hand, larger number of units should be build using conventional technologies, being more efficient when it comes to Mass Production.
Studying the different limitations of Additive Manufacturing, it should be possible to create prototypes that have really similar properties to the final product. In the current case, the biggest limitation related to the bending or torsional beam is that they cannot be totally hollow.

Certain geometries, with steep vertical angles, and hollow parts are impossible to produce without any supporting structure. However, one of the requirements of this thesis is to produce hollow parts without having to remove any supporting structure inside the structure, which means that hollow beam cannot be hollow anymore. Instead of developing a method to produce hollow beams with a removable supporting structure, the main goal is to achieve that the supporting structure is a structural part of the beam. [1]

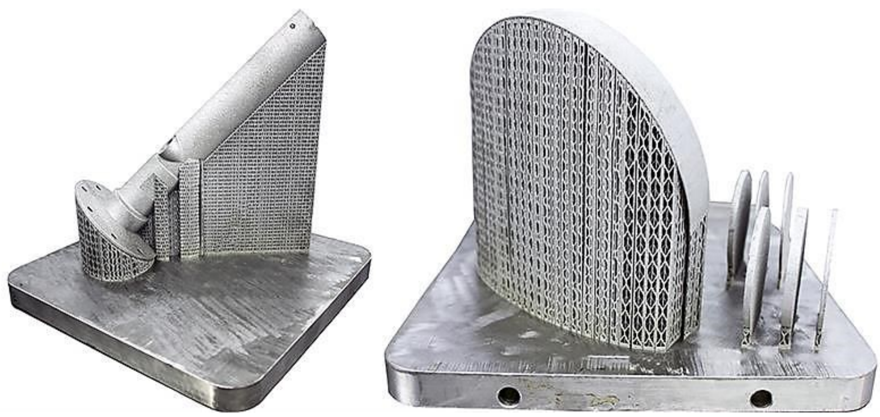


Figure 1.1: Additive Manufacturing Parts with supporting structures. [1]

The main impact that this method may have is allowing fast production, using AM technologies, of hollow parts and prototypes that do not need to remove any supporting structure. This makes the production faster and adds strength to the part while keeping a similar mass, only if the method is applied correctly and the technologies allow it.

1.2 Objectives

The main objective is to develop a design method for AM that will allow building hollow or semi-hollow parts. The method should work for any hollow AM part, not depending on sizes, shapes or angles.

This is an experimental thesis, based on experimental work: 3D model design, Finite Element Simulation, Fused Deposition Modelling specimen production and specimen Tests in the laboratory. This means that this thesis is written as a report of all the experiments and practical work done.

1.3 Scope

The scope of the thesis is to produce and test, at least, a hollow beam produced by FDM technology. To achieve this, it is necessary to follow these steps incrementally:

- Study the Additive Manufacturing technologies, especially PBF, for metals, and FDM, for thermoplastics. The project will use FDM because it is faster and cheaper. However, the method designed must work for most technologies and especially for PBF.
- Study the anisotropy of AM parts, theoretical and research part.
- Study of semi-hollow structures found in nature.
- Design of 3D models, being aware of AM limitations and not needing any supporting structure. It must be an iterative process that reaches the limit of the applied FDM machine, trying to produce as hollow specimens as possible.
- Simulate a Compression test with the 2 final 3D models to determine which the best directions to test the bricks are. The bricks are the same semi-hollow shaped profile as the beams, but shorter.
- Simulate a Bending test with the 2 final 3D models to compare them. The main comparison must be Strength decrease against Mass reduction.
- Test the bricks in a destructive Compression test to analyse specimens' anisotropy.
- Test the bending beams in a destructive Bending test to analyse how geometry affects the strength of the 2 final specimens.
- Correlate the Simulation results with the Experimental test results. In case they do not correlate, study the possible reasons and propose solutions.
- Study possible improvements for the specimens produced and also for the method designed.
- Analyse future improvements, further studies and experiments that can be done in the future.

2 Theorical background and overview of literature

2.1 Additive Manufacturing Introduction

First of all, it is necessary to understand the importance of Additive Manufacturing in the present and future of product generation and development. This chapter is focused on describing what it is, why it is so important and it also describes two widely used technologies that could use the designed method.

2.1.1 Definition

Additive Manufacturing, also known as 3D printing, is currently one of the most popular technologies and is undoubtedly the most disruptive of recent years. It is defining and will continue to define the development of all types of industry during at least the first decades of the 21st century. [2]

The principle of AM is the layer by layer manufacture, a way of producing elements that, starting from a 3D file/model and dividing it into slices, is able to shape an entire element from the progressive manufacture of each one of the layers that form its geometry, using the precise amount of material necessary to make each one.

2.1.2 Applications

There are currently two generic applications where AM is widely known: product development and manufacture of final parts.
For the first time, there is a technology capable of supporting the design and engineering process with the manufacturing of individual parts and prototypes that is not constrained by the technical limitations of traditional technologies, producing them quickly and at reduced cost.

AM technologies have an application in each and every one of the steps that define a product development process. From this perspective, it can be used in:

- Concept Stage: Development of non-functional prototypes. It is fast, cheap and a lot of different materials can be used in this stage.
- Design and engineering: Once various concepts have been evaluated and one or several design concepts have been selected, AM technologies can be used to produce demonstrators and prototypes for engineering testing.
- Prototyping and testing: Once the design and engineering have resulted in a complete and developed product concept, AM technologies allow the realization and testing of functional prototypes.

The main advantage of its usage during Design, Prototyping and Testing stages is the elimination of the limitations of other technologies, allowing a shorter manufacture time, a rationalization of the cost and a lower cost of design changes. Additive Manufacturing is here to stay and will be a basic tool for designers and engineers in any field of technical development.

2.1.3 Additive Manufacturing compared to Traditional Manufacturing

AM is a new technology compared to the traditional ones and obviously there is a 3D-printing technologies hype. Nowadays, it is well known what its advantages are. However, it is not clear if it as good as Traditional Manufacturing (TM) technologies when it comes to final product parts.

The following description of advantages and disadvantages may answer this question.

Advantages:

- Part complexity: Being a layer-by-layer fabrication process, this technology is capable of rendering geometries of great complexity, with cavities and forms not possible to obtain with traditional technologies.
- Lead time (First part/Short series): The ability to generate a part simply from a 3D file makes these technologies unbeatable when manufacturing a first part, since it eliminates the need for other technologies, such as tools or moulds.
- Customization: Since no additional tooling is required, the manufacture of a modified part is as straightforward as the manufacture of the original design.
- Lower fixed costs for product development and first product series: As no additional investments are required, it is possible to considerably lower the initial cost of producing prototypes and first series of products.

Disadvantages:

- Detail/Precision: Traditional technologies such as subtractive manufacturing have significantly more accuracy than additive manufacturing technologies. TM technologies can be an order of magnitude more precise.
- Long batches: Although aspects such as speed and raw material costs are being continuously improved, when aiming to produce large amounts of parts, AM technologies tend to be slower and more expensive than traditional ones.

- Range of available materials: Although the range of available materials is continuously improving, especially in the area of plastics and metals and, more recently, ceramics; it is still limited compared with the materials available for other technologies.
- Quality and certification: As a relatively new technology, there are still some uncertainties and a lack of standards for assuring the long-term quality of the manufactured parts.

It can be said that AM is one of the most revolutionary technologies of the 21st century. It definitely changed the way new products are designed. However, at this moment, it can be seen that it will need to improve a lot in some aspects to beat TM, which is incredibly effective with big lots and final parts.

2.1.4 Manufacturer opinion (BMW)

With the aim of showing how does it really work in the industry, this section shows a main manufacturer opinion on the AM technologies, also commenting its future. BMW claims they already recognised the importance of this technology in the 90s. [3]

They argue that the biggest advantage of AM is that the process offers a high degree of flexibility in creating the form. Components with complex structures, which are otherwise difficult to produce, can be manufactured quickly and easily using AM technologies while delivering the desired quality. Adding that, they use additive manufacturing in various areas. Now it is often used where tailor-made and sometimes very complex components are required in small quantities. This is especially the case in pre-development, vehicle validation, and testing, or in concept and show cars. Completely new vehicle developments are a particular highlight for these technologies. For example, in the case of BMW new *i* vehicles for which no predecessor vehicles were available. Therefore, the first prototype vehicles had to be mostly produced with additive manufacturing.

According to them, the greatest challenges for AM are related to the process itself and material costs. At present, AM is not yet suitable for large-scale production. However, they see a positive development here. New, two-dimensional technologies are an essential key to this.

To give an example, a main final part that BMW is currently producing using AM is the mounting for the top cover of the new i8. The main advantage of this part is that it is stronger and weighs less than the same part produced using a traditional casting process.

2.1.5 Available Technologies

There are different technological approaches of applying AM. The layer by layer concept can be applied using different material and processes. Some of them are Fused Deposition Modelling (FDM), Powder Bed Fusion (PBF), Direct Energy Deposition, VAT Polymerization, Material Jetting, Sheet Lamination and Binder Jetting. [2]

This thesis is mainly focused on FDM, because it is the technology used for the bricks and beams from the experiments, and PBF, because in case the method for producing semi-hollow beams prototypes would be used, this would be the technology used.

2.1.5.1 Fused Deposition Modelling

In this technology, a plastic filament is melted and extruded through a nozzle and then laid down onto the previous layer, instantly cooling and solidifying. Existing layers act as a foundation for additional extruded material and the machine creates the object bottom up, layer by layer. [2]

It is a really affordable and accessible technology. However, it is important to understand the limitations of this technology. Due to a lower cohesion between layers, the produced parts are liable to anisotropy in the Z axis, building direction, with poor resistance to pulling tensions perpendicular to the layer's direction. Layer thickness results in poor surface finish and tolerances and support structures may be required to prevent newly deposited layers from drooping during the cooling process.

The following image show more clearly how this technology works:

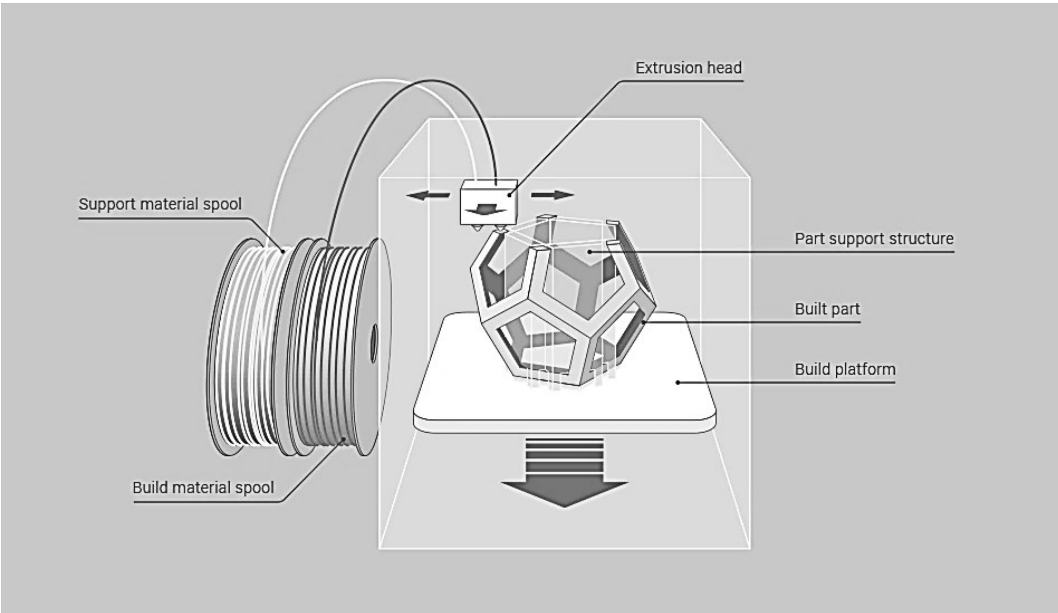


Figure 2.1: Fused Deposition Modelling [4]

2.1.5.2 Powder Bed Fusion

This technology includes: Direct metal laser sintering (DMLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM) and Selective Laser Sintering (SLS). [2]

The principle of this technology is that a fine layer of particles material is deposited and sintered or melted by the action of a selective heating source. Then, a new layer of particles is added and selectively sintered or melted. This process has to be done for every layer of the part.

The following images show more clearly how this technology works:

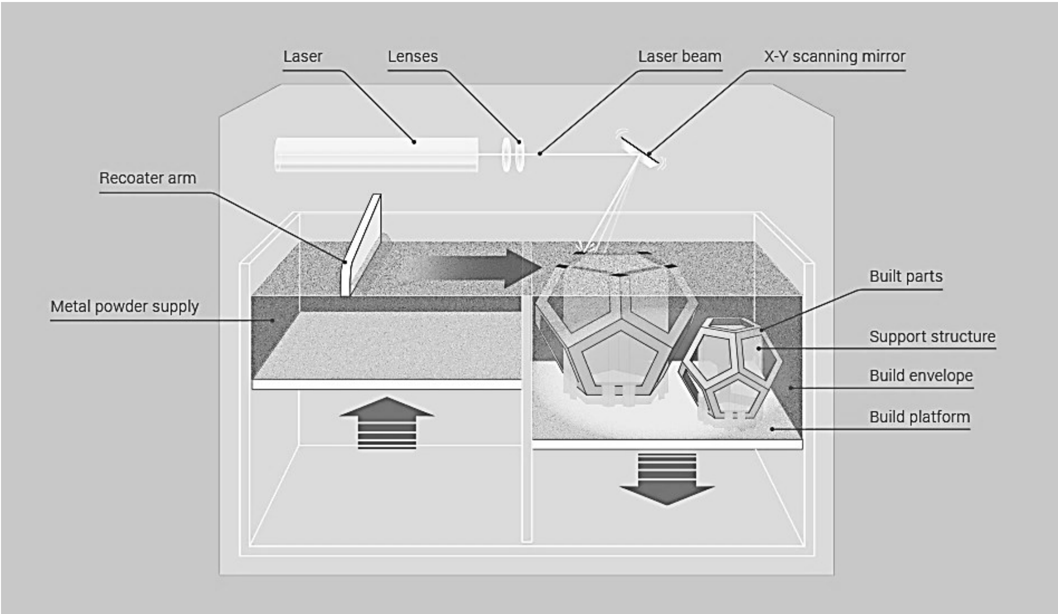


Figure 2.2: Selective Laser Melting technology [4]

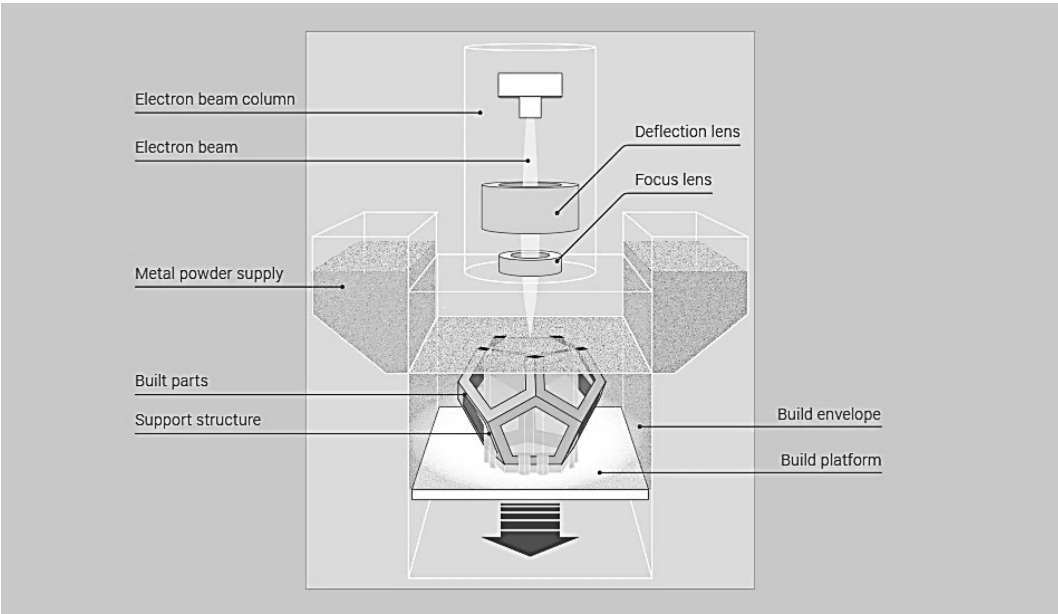


Figure 2.3: Electron Beam Melting technology [4]

2.2 Additive Manufacturing Anisotropy

Building direction, perpendicular to the layer direction, is a crucial parameter when producing AM parts. It is something inherent to these technologies and it is really important to consider. In the next sections, 2 different studies show the anisotropy effect using the same material, ABS, but different AM technologies.

2.2.1 Fused Deposition Modelling

The university of Bucknell and Duke, in the USA, performed tensile, compressive and bending tests using the same specimen geometry, different for each test. However, the building direction was different in order to analyse the anisotropy effect. A mixed mesh was also included in the experiment. The specimens were produced using FDM technology. The following images show the specimens geometries and the building directions: [5]

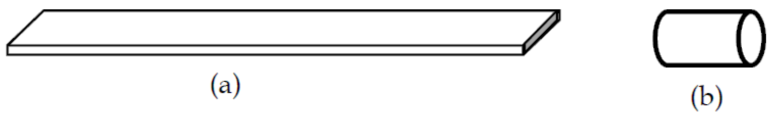


Figure 2.4: Specimen geometries associated with each test.
Tensile (a), Compressive (b), Bending (a). [5]

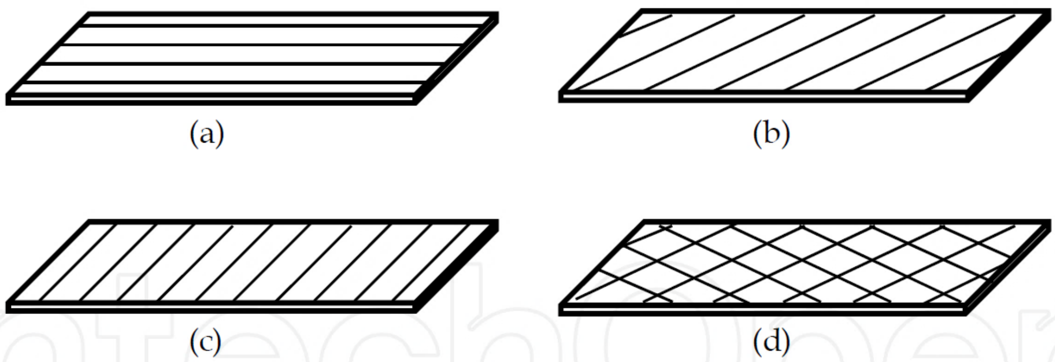


Figure 2.5: Four different printing orientations studied.
Longitudinal (0º) (a), Diagonal (45º) (b),
Transverse (90º) (c), Default (+45°/-45°) (d). [5]

The results of the study were really interesting, showing the big influence of the building direction and anisotropy of the AM parts. The numerical results are shown in the following table, Table 2.1. It can be seen that there is a big difference between 90º and 0º when there is tensile or bending stress. The building direction does not affect that much when the specimen is under compressive stress.

Table 2.1: Tensile, Compressive and Bending/Flexural test results [5]

Tensile Test			
Raster Orientation	Mean Yield Strength (MPa), Std Dev	Mean Ultimate Stress (MPa), Std Dev	Mean Effective Modulus (MPa), Std Dev
Longitudinal (0°)	25.51, 0.73	25.72, 0.91	987.80, 19.98
Diagonal (45°)	15.68, 0.27	16.22, 0.27	741.78, 20.28
Transverse (90°)	14.35, 0.08	14.56, 0.05	738.77, 7.91
Default (+45°/-45°)	18.90, 0.53	19.36, 0.39	768.01, 33.31
Compressive Test			
Raster Orientation	Mean Yield Strength (MPa), Std Dev	Mean Ultimate Stress (MPa), Std Dev	Mean Effective Modulus (MPa), Std Dev
Longitudinal (0°)	28.83, 1.16	32.32, 0.58	402.64, 03.64
Diagonal (45°)	24.46, 0.30	33.43, 0.20	417.20 10.06
Transverse (90°)	29.48, 0.75	34.69, 0.99	382.21, 10.31
Default (+45°/-45°)	28.14, 0.64	34.57, 0.86	410.44, 11.23
Bending Test			
Raster Orientation	Mean Yield Strength (MPa), Std Dev	Mean Ultimate Stress (MPa), Std Dev	Mean Effective Modulus (MPa), Std Dev
Longitudinal (0°)	34.2, 2.6	38.1, 2.3	1549.0, 327.3
Diagonal (45°)	21.3, 0.2	25.7, 0.6	1250.0, 036.1
Transverse (90°)	20.8, 0.9	23.3, 1.6	1269.7, 149.6
Default (+45°/-45°)	26.5, 0.7	32.2, 0.5	1438.6, 034.7

2.2.2 Selective Laser Sintering

A group of engineers at Veryst Engineering, Boston, performed a really interesting experiment building the same elastic test ABS plastic specimens in different directions. The geometries were the same but the orientation varied from 0º to 90º. Figure 2.6 shows how the specimens were printed using SLS technology [7].

One of biggest the challenge of designing with AM polymers is considering their anisotropic mechanical properties. These materials fail more easily when loaded along the build direction due to weak interlayer bonding. An engineer could conservatively assume the weakest properties for every orientation, but assuming this, counters the goal of using AM to enable highly-optimized part geometries. Moreover, maximizing AM part performance requires a detailed understanding of this mechanical anisotropy.

The specimens were tested to failure measuring Stress at Failure and Strain to Failure. The best building direction appears to be 60º, while angles wider than 45º have good results. Figure 2.7 shows the graphics of the results.

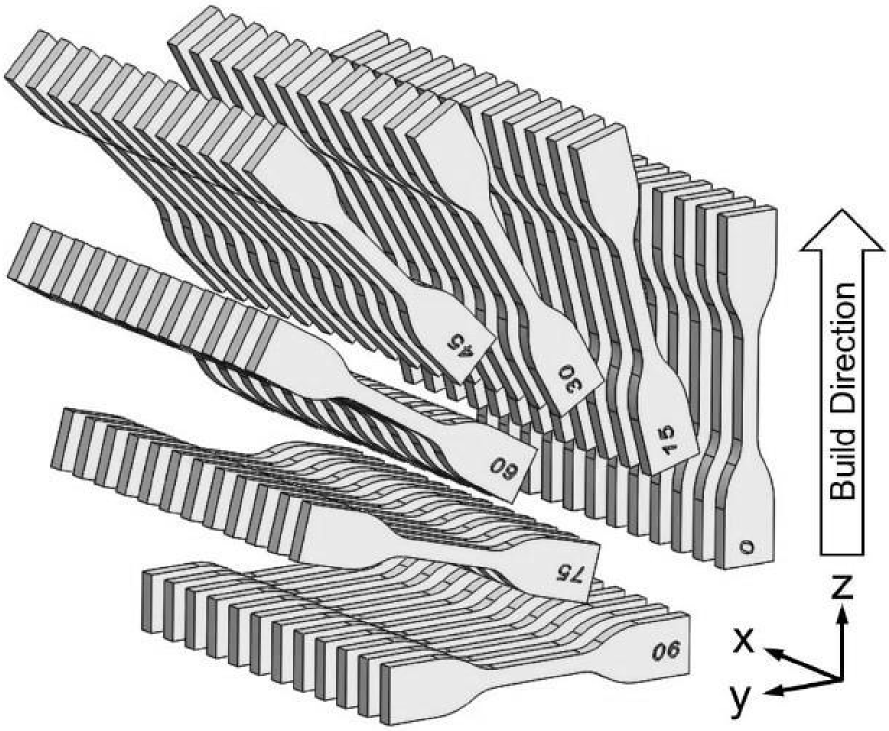


Figure 2.6: Tensile specimen orientations [7]

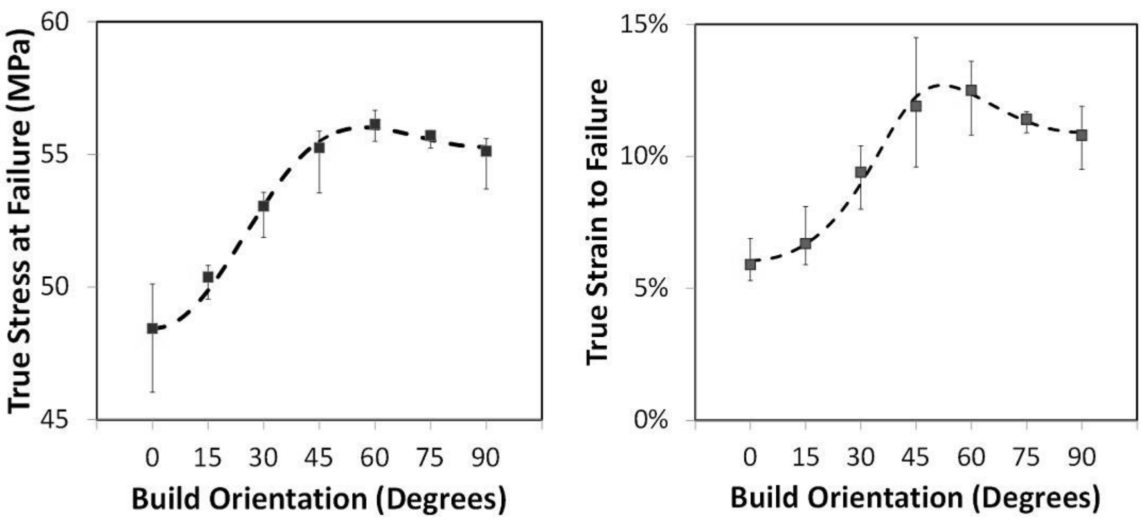


Figure 2.7: True stress and strain at failure as a function of build orientation [7]

As it can be seen in the graphics, the building direction has a great impact on the specimen strength, this is why it would be a really important factor when building the semi-hollow beams.

Another experiment, also showed that building in the 60º direction increased a 58%, the energy required the break a bending beam, compared to 0º building direction, and a 16%, compared to the 90º building direction. [7]

2.3 Design of hollow structures. Nature Inspiration.

In order to find inspiration to design an AM method to build hollow parts, it is really interesting to look at natural hollow internal structures. In the nature, it is possible to find structures that seem totally solid but that actually are not. Two great examples of that are wood and bones. Both of them have to support stresses and both are anisotropic too.

2.3.1 Wood

Wood possesses a cellular, three-dimensional microstructure and it can be considered a natural composite material. The different type of cells form the internal structure shown in the following figures, Figure 2.8 and Figure 2.9. Similar to AM parts structure, wood is and anisotropic material that has good mechanical properties in the X axis, poorer properties in the Y and Z axes.

These anisotropic properties make wood perform well subjected to bending stresses, if the bending moment is applied in the Y or Z axis. This is why wood beams are placed this way. Being inspired by this structure, it would be a good idea to think of a constant profile for the AM beam, two dimensions profile that would be constant through all the length of the beam.

The designed profile should be semi-hollow, like wood internal structure, adding more holes than material. Also, the fibres should be placed in the X direction, placing them in the 90º direction, not the best direction but much better than 0º.

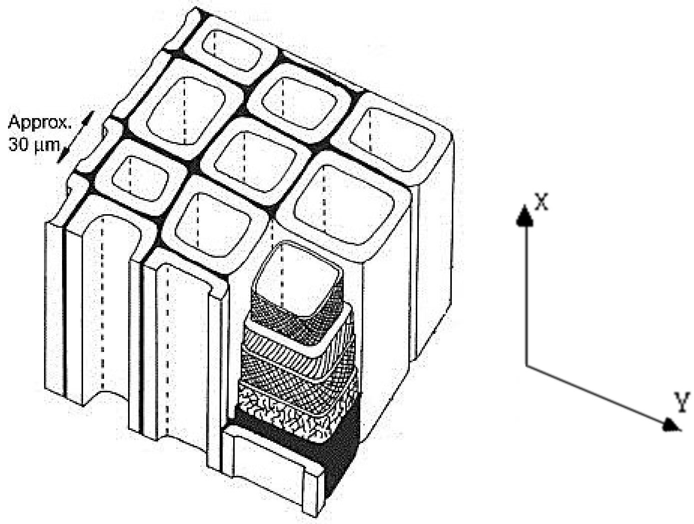


Figure 2.8: Wood internal microstructure [12]

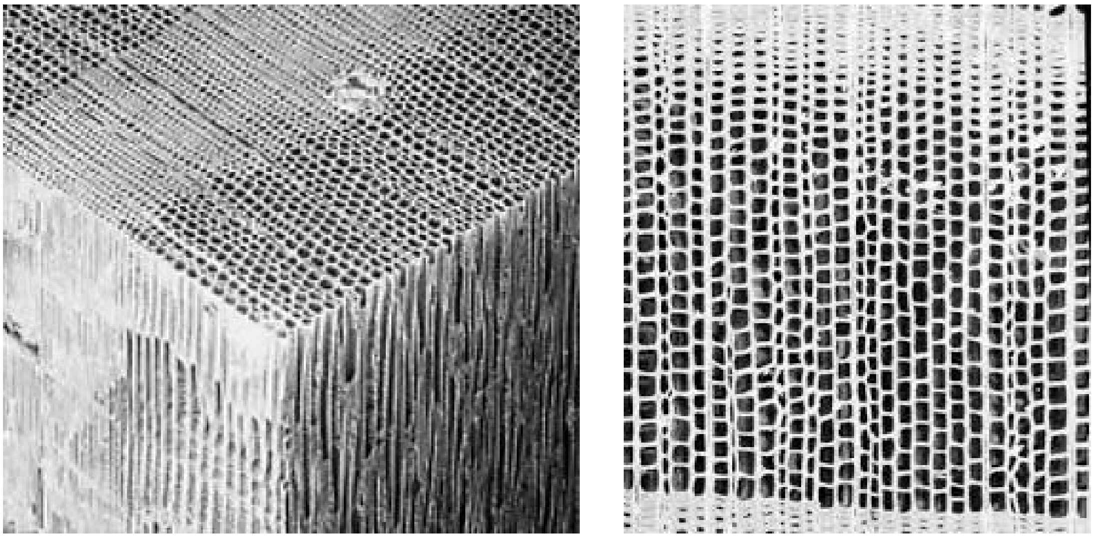


Figure 2.9: Cell structure of softwood, magnified 50x [13]

2.3.2 Bones

Similar to wood, bones have a semi-hollow internal microstructure. They have a really interesting internal structure. Bone tissue is placed in the right place according to the stress applied. A clear example of that is the thigh bone or femur. It is dense and highly meshed in the head and lower extremity while the body or shaft is similar to a tube. Another great example of that are bird bones, Figure 2.10, which are incredibly hollow and light.

What can be learned from bones is that when they are subjected to bending stresses the mass is placed far from the centre, X axis, giving the bone general low density and higher moment of inertia for the Y and Z axes. This can also be applied to any beam, produced by AM or not.

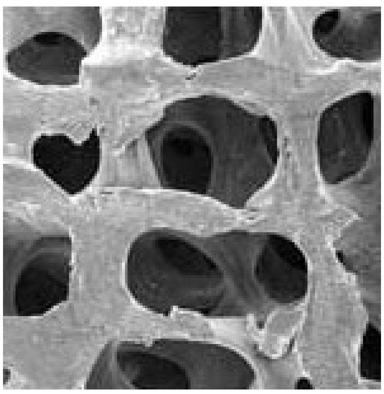


Figure 2.10: Human Bone Microstructure [14]

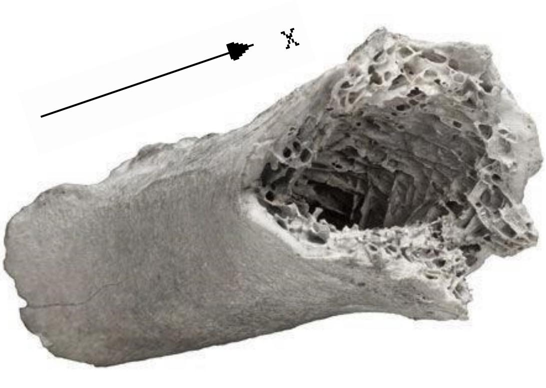


Figure 2.11: Bird Bone [14]

The following image, Figure 2.12, shows how an AM femur head would look like.

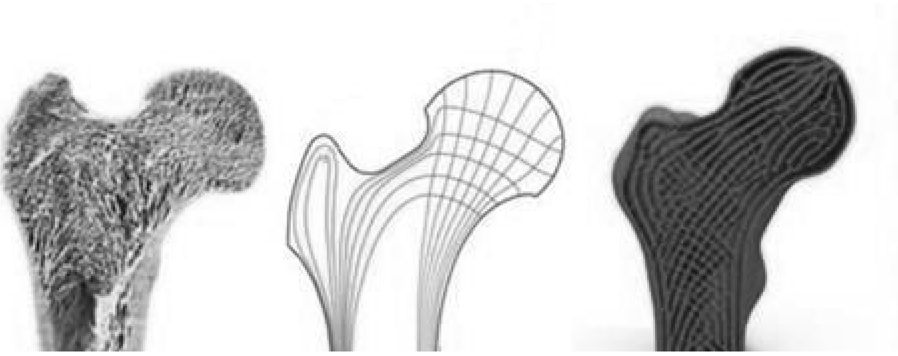


Figure 2.12: Infill Optimization for Additive Manufacturing -
Approaching Bone-like Porous Structures. [15]

3 Design of the Beam

This chapter is totally focused on the design of the semi-hollow bending beams. The considerations, limitations and design parameters are explained in detail. Every design decision was made after understanding the principles of AM and after completing the theoretical background of the thesis.

3.1 Bending Beam subjected to Pure Bending

Like all technologies, they have their *pros and cons* and AM is not an exception. As it is known anisotropy clearly defines the strength of the part. However, used wisely, concentring the tensile stresses in the perpendicular direction of building, can increase drastically the strength of the part.

The part desired in this thesis is a semi-hollow beam that works under bending stresses. To simplify the stresses, the bending beam will be tested applying three-point bending arrangement. The following images, Figure 3.1 and Figure 3.2, show how it will be applied to the bending beam.

It also can be seen that the tensile and compressive stresses are oriented in the direction of the beam, X axis. This means that the worst possible direction to build the beam would be in the X direction, 0º building direction, as it was seen in the previous chapter. However, this would be the easiest way of building the beam, allowing it to be completely empty.

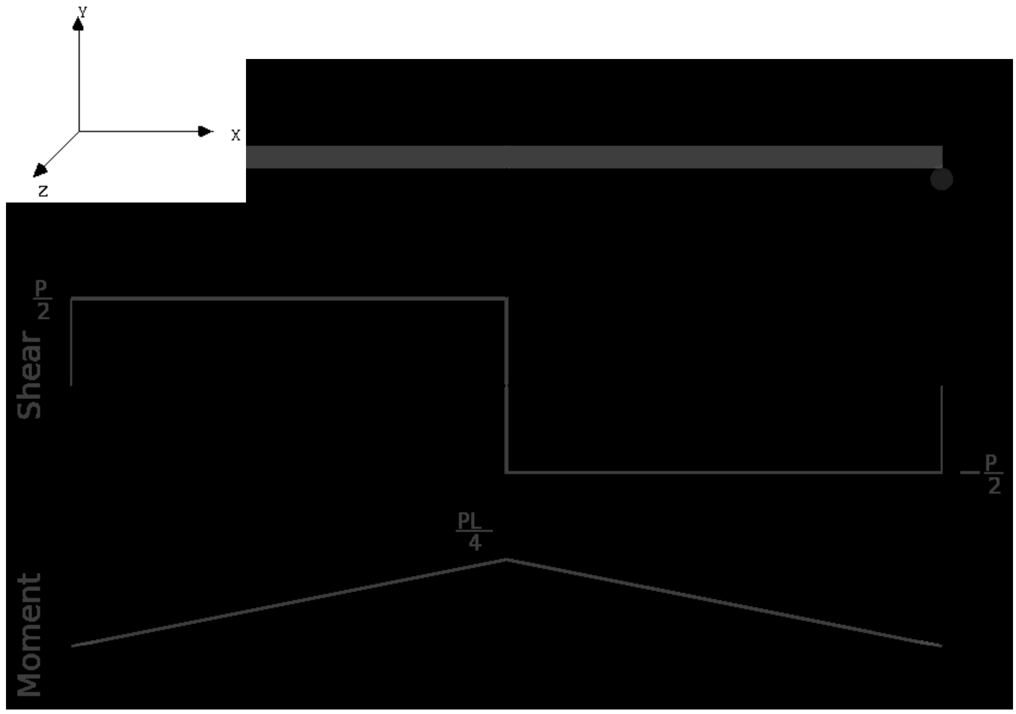


Figure 3.1: Three-point Bending characteristics [17]

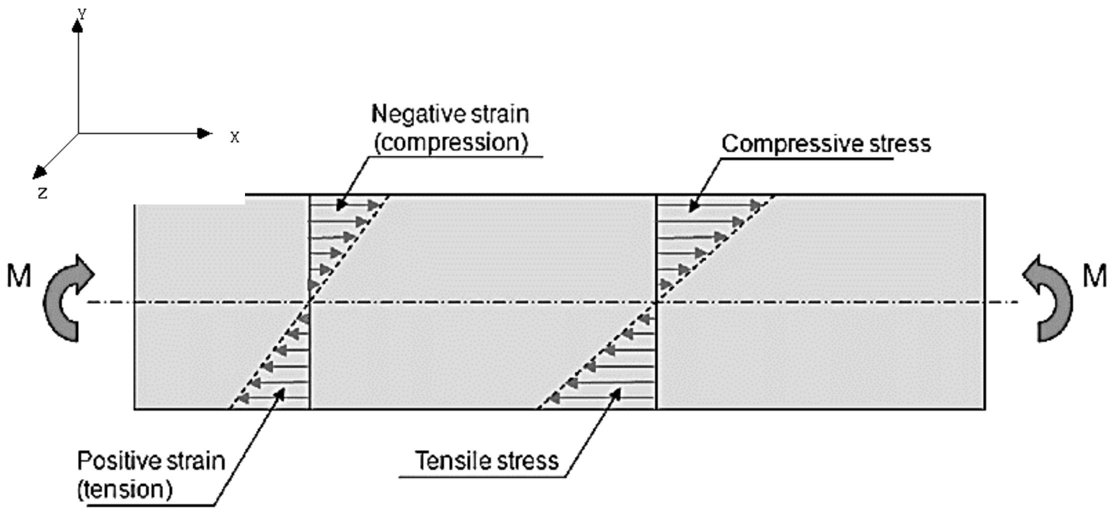
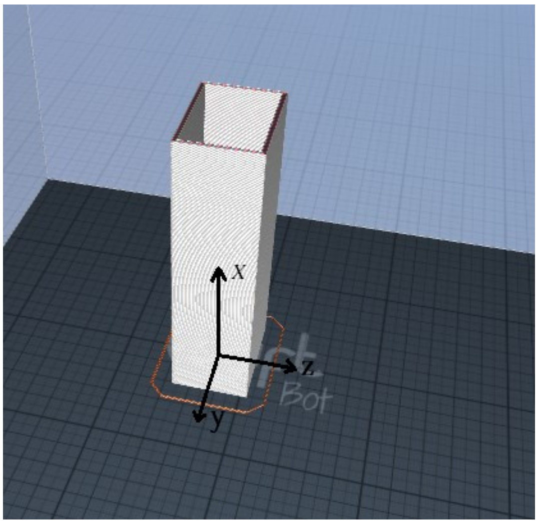


Figure 3.2: Beam with constant profile cross section subjected to pure bending. [17]



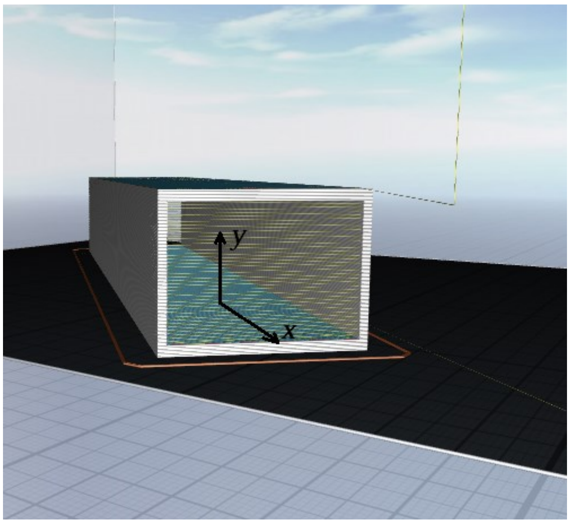


Figure 3.3: Hollow beam built in the X direction (Left).
Hollow beam built in the Y direction (Right)
[CraftWare 3D printing Software]

On the left, Figure 3.3, there is a hollow bending beam built in the X direction. This direction would be great because it allows the beam to be totally empty. However, due to weak interlayer bonding in the building direction. it is not an option.
On the right, there is a hollow bending build in the Y direction. It is clear that this beam cannot be produced without supporting structures. It is impossible to build, using FDM technology, because the top layers cannot be produced without adding any material or supporting structure below, in the hollow part. The objective of this thesis is to build a beam as hollow as possible designing the necessary internal structures.

In the previous chapter, it was seen that the best building direction is 60º, although that 45º to 90º have good results. Building the beam in the 60º, could be possible adding supporting structures below the beam, as seen in Figure 1.1. However, another goal of this thesis is to build the beam without any unnecessary supporting structure. The beam has to be functional without removing any supporting structure.

After these considerations, the only real option is to build the beam in the 90º direction, Y direction, seen in Figure 3.3 on the right. Depositing the material or filament in the direction of the stresses, will increase the strength of the part. It is the same as orienting the fibres of a composite material in the best possible direction.
Finally, after fixing the direction, the only parameter that can be adjusted is the shape of the semi-hollow profile. It will define completely the design.

3.2 Design Parameters

In this section, the fixed parameters are defined and then, after, the variable parameters are defined according to the fixed ones.

3.2.1 Fixed Parameters

There are some fixed parameters that have to be set and cannot be changed afterwards:

- Beam Dimensions: 40 x 30 x 180 mm
  According to the FDM machine or 3D printed used these dimensions are reasonable.

- Edge Width: 2 mm
  Proportional to the beam and standard hollow beams.

- Printing Direction: Y direction, 90º.
  As said before, it is not the best direction but is the only one that can be used without further supporting structures. Moreover, the mechanical properties are not that worse or different from the 45º or 60 º directions.

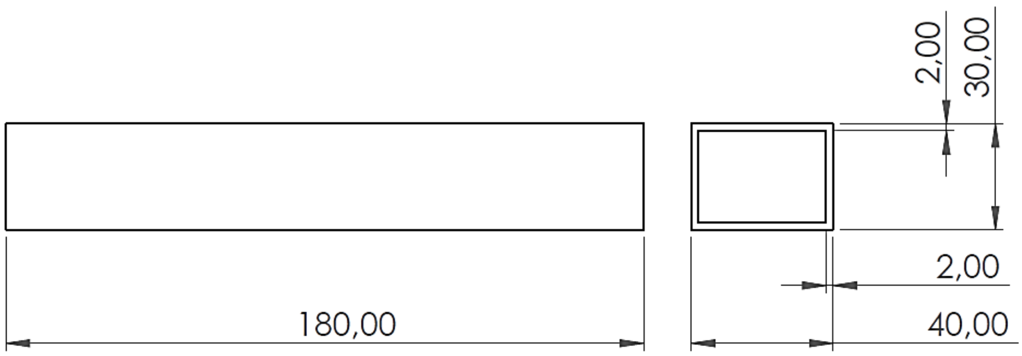


Figure 3.4: Beam dimensions drawing [SolidWorks Drawing]

3.2.2 Variable Parameters

Once the fixed parameters are decided, it is the moment to think and understand which are the variable parameters and design possibilities. The needs of the design are:

- Low Mass: It should be as hollow as possible. However, mass and stress at failure are inversely related.

- High Moment of Inertia in the Y axis (I_y): The bigger the I_y the better the properties of the specimen when it is subjected to pure bending.

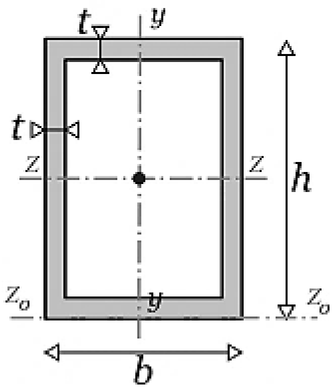


Figure 3.5: Moment of Inertia of a Rectangular Tube [18]

$$I_y = bh^3 / 12 \; - \; (b-2t)(h-2t)^3 / 12 \qquad (3.1)$$

If the beam is desired to perform well when subjected to bending, it should have a high moment of inertia in the Y axis. This means having more mass in the upper and bottom edges and allowing the centre to be hollow. Adding mass to the side edges does not make any important difference. However, it improves the performance of the beam subjected to torsional stress.

- Building or Printing Angles, Overhang: It is known that angles wider than 45º need a supporting structure. The angles used should be around 30º, being conservative, but it is possible that the design could improve increasing the angles until 45º. It can be seen in the image, Figure 3.6, that the 70º angle part loses quality if there is no supporting structure added.

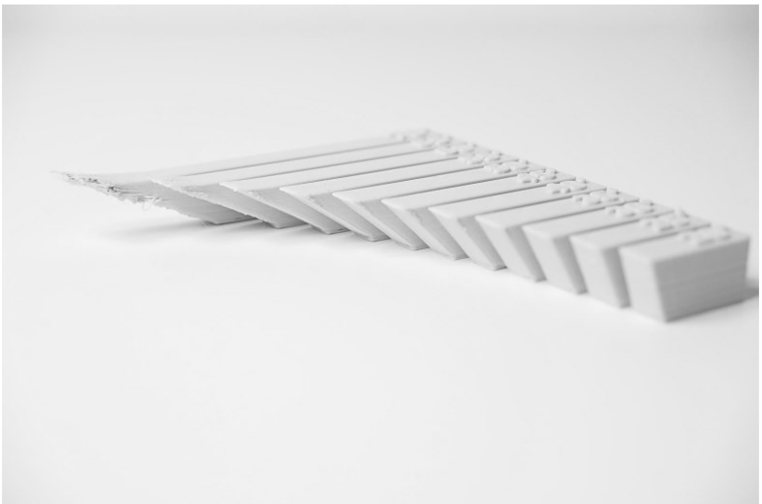


Figure 3.6: Overhanging angles, 70º to 15º [19]

3.3 Profile Development and Profile Iterations

After considering all the limitations and parameters and being inspired by internal microstructures found in nature, it was thought that the best way to fill the beam would be a patterned structure. The shape of the pattern should be easy to print, avoiding wide overhanging angles and big hollow parts.

The first trial was to design a pattern of really small holes that might act as a microstructure. However, the width of the layer was set at 0.3 so it was the minimum dimension for the models. At some point, it was decided that the minimum dimension should be 1 mm, fitting 3 filaments together.

The holed shapes needed narrow overhanging angles on the sides so it was decided that the best shape for that was a rhombus, with narrow angles at the top and at the bottom and wide angles at the sides.

The following images show the profile design iteration process:

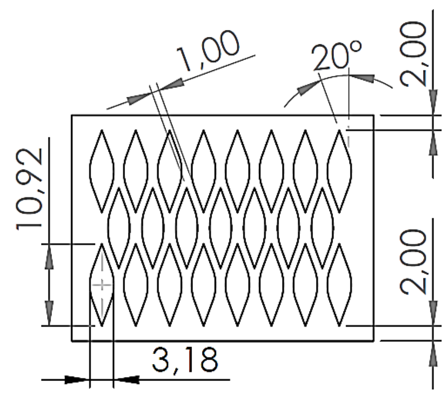


Figure 3.7: Profile 3.3.2

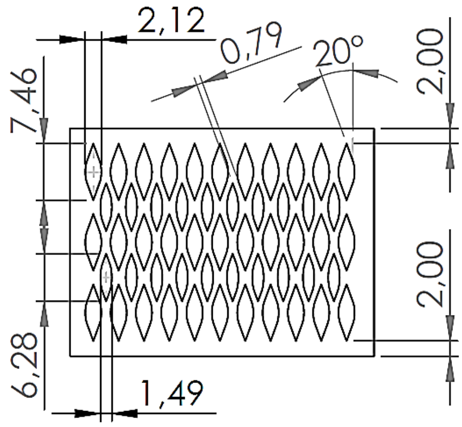


Figure 3.8: Profile 3.3.3

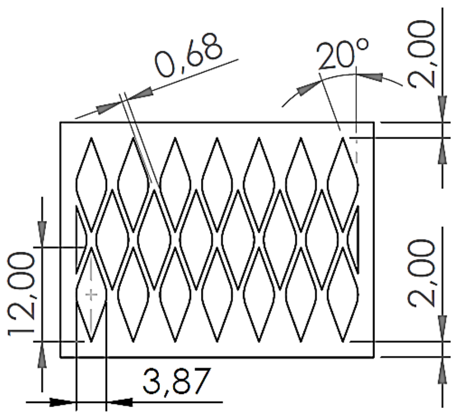


Figure 3.9: Profile 4.0

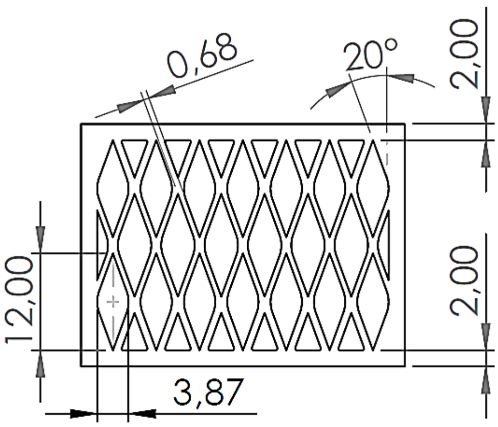


Figure 3.10: : Profile 4.2 (upper part impossible to build, 90º angle)

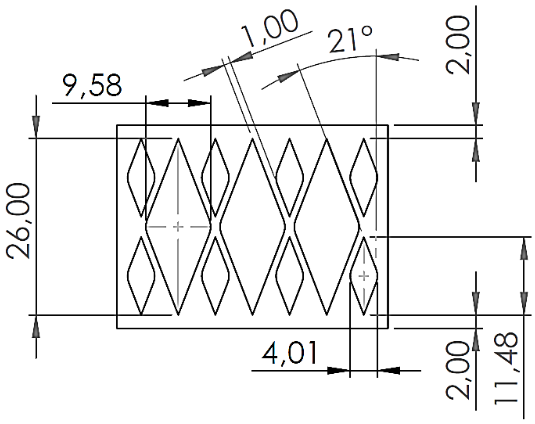


Figure 3.11: Profile 4.5

The following table shows the different design characteristics:

Table 3.1: Profile and Model properties

Model	Area [mm^2]	Moment of Inertia (I_y) [mm^4]
3.3.2	661.97	689,3
3.3.3	764.30	684,7
4.0	652.47	689,5
4.2	558.99	566,0
4.5	611.53	674,3

All the profile models are designed under the same method or principle, a rounded rhombus pattern. Profiles 3.3.2 and 3.3.3 are very similar but the 3.3.3 only increases a lot the area, increasing mass, and only improves a little bit the moment of inertia. 3.3.3 does not improve 3.3.2. Profile 4.0 adds half rhombus on each side to reduce mass in the centre, without affecting the moment of inertia; it could also be applied on 4.5. Profile 4.2 is impossible to build due to 90º angles on top, although this could work on the bottom of the part. However, it is better to have a symmetric beam. Finally, profile 4.5 is an iteration of 3.3.2, joining four rhombuses in one and making the edges shaper.

At the end, the profiles picked for the experiments were 3.2.2 and 4.5. It is possible that these would not be the best ones but they are really different. 3.2.2 is denser but has a great moment of inertia. On the other hand, 4.5 reduces the density a 7.55% but also the moment of inertia a 2.17%. Choosing profiles that are more different may give a clearer result on what is more interesting, mass reduction or high moment of inertia.

4 Methodology

The experimental part is divided into 2 parts: bricks production and compressive test, to analyse anisotropic properties of AM technologies, and beams production and bending test, to determine if bending simulation and bending test have similar results when the beam is produced using an AM technology.

In order to have computational results and experimental results, 3D model simulations, compression test and bending test have been performed. The 3D model simulations have been used to decide which would be the best direction to test the bricks in the compression test and to have bending simulation results, comparing the 2 beams model tested. The compression test was performed to determine how much the printing direction affected the structure of the beam. Smaller specimens were printed with the same profile shape as the final beams but shorter, this is why they are called bricks. The bending test was performed to compare the results of the 2 types of beams produced. According to simulation, the results should be close but due to the effect of the material anisotropy and AM technology limitations. However, the results are really interesting.

In this chapter, the methods used to test the specimens, both simulation and physical test, are explained, so as the procedure from the profile design to the actual specimen production, using bricks for the compression test and beams for the bending test.

4.1 Specimen's Preparation

The technology used to produce the specimens was Fused Deposition Modelling, also known as 3D printing for plastics. As explained in chapter 2.1.5.2, it is an affordable and accessible technology that is perfect to check if the designed method works to afterwards test it with another technology like Powder Bed Fusion for metals. The material used for the specimens was PLA thermoplastic.

The FDM technology biggest limitation is low cohesion between layers. The direction of printing, Y axis seen from the part or Z axis seen from the printer, has low resistance to pulling tensions. This is why the filament was printed in the direction of the tensile stresses. In Figure 4.1, it can be seen how the filaments are correctly placed in the stress's direction.

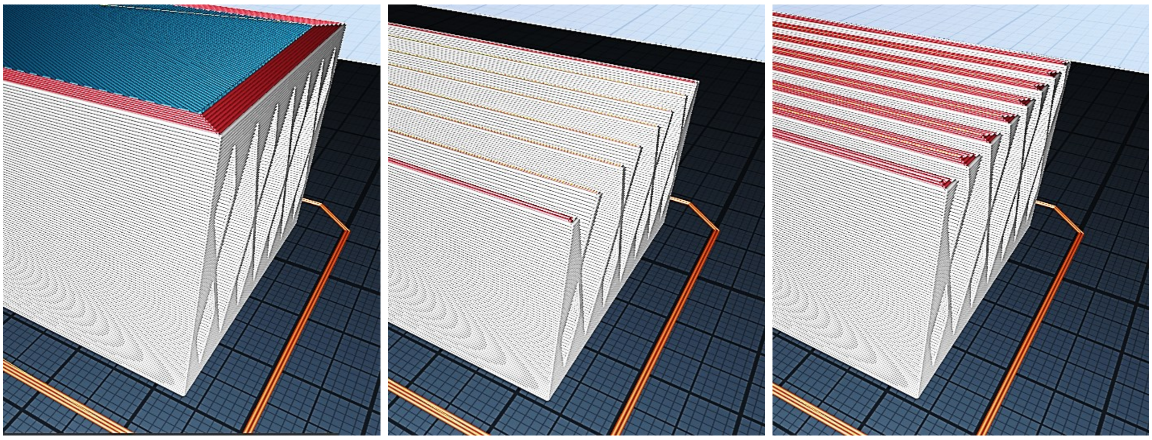


Figure 4.1: GCode Visualizer Images in different layers [CraftWare]

4.1.1 Compression Test Specimens

For the compression test, it was decided that there was no need to produce the whole beam. Therefore, bricks with the same profile shape were produced. They were named bricks because instead of having a 180 mm length these were only 30 mm long.

In order to the test anisotropy effect, three 3.3.2 bricks were printed in the X direction and three 3.3.2 bricks were printed in the Y direction. In addition, three 4.5 bricks were also printed in the Y direction to compare the model 3.3.2 and 4.5.

4.1.2 Bending Test Specimens

For the bending test, the whole 180 mm long beam was produced. Originally, two 3.3.2 beams and two 4.5 beams were produced. It would be great to have more specimens but, at first, they were not easy to build and it could take more than a day to print a single beam.

4.2 Simulations

The simulations were performed using the SolidWorks Simulation tool. The compression test simulations were done in three axes to decide which direction should be the most interesting to test. The bending simulations were done to compare the simulation results with the experimental results. Note that all simulations were done considering that the material was isotropic because it would be too hard to define the FDM printed specimen anisotropy model.

4.2.1 Compression Test Simulation

The compression test simulation was performed on the 3.3.2 brick, in the three axes and with the same conditions. The force, 1000 N, was applied in one side and the fixtures in the opposite, imitating the real test conditions.

The aim of this simulations is to understand which is the best direction to do the compression test, it will be explained in the chapter 4.3.1 Compression Test Experiment, and also see how the structure of the beam acts subjected to lateral pressures.

The following table shows the finite element meshing conditions:

Table 4.1: 3.3.2 Brick Mesh information [SolidWorks Simulation Report]

Parameter	Definition
Mesh Type	Solid Mesh
Mesher Used	Blended curvature-based mesh
Jacobian Points	4 points
Maximum Element Size	1.5 mm
Minimum Element Size	1.0 mm
Mesh Quality Plot	High
Total Nodes	159157
Total Elements	95850

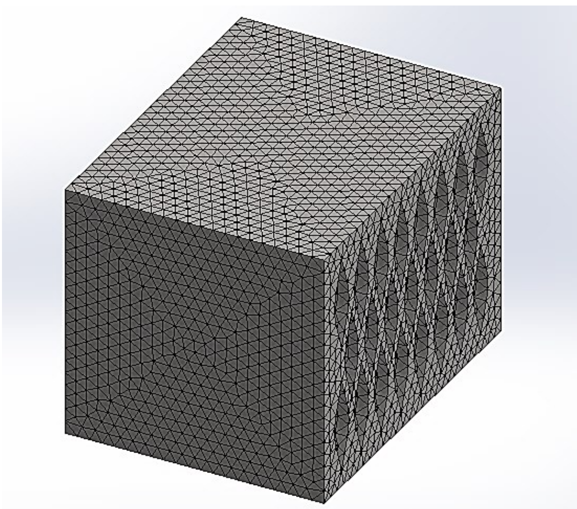


Figure 4.2: 3.3.2 Brick Simulation Mesh [SolidWorks Simulation]

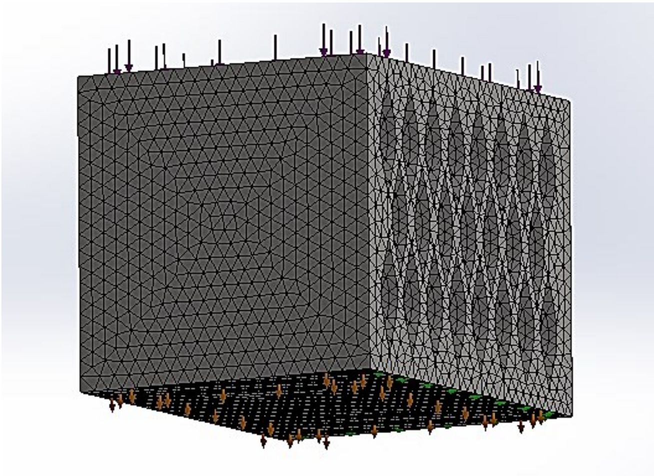


Figure 4.3: 3.3.2 Brick Y axis Compression Test Simulation Mesh and Boundary Conditions. Fixed Bottom Surface (orange), Fixed Edges (green), Load (purple) [SolidWorks Simulation]

4.2.2 Bending Test Simulation

The bending test simulation was performed on both the 3.3.2 and 4.5 beams with the same conditions. In order to simulate bending, the same length bricks and fixtures were used. The brick, that pretends to be the beam, was fixed on an X plane, cross section plane. It was also fixed only in the bottom and one side, allowing it to expand due to compression and squeeze due to tension. The pressure gradient shown in the following figure, acts as the bending moment, applying tension, 1000 N, in the upper part and compressing, 1000 N, in the bottom part.

The aim of these simulations is to compare them with the real bending test and see which the results of the two beams are, in simulations and real tests.

The following table shows the finite element meshing conditions:

Table 4.2: 3.3.2 Beam Mesh information [SolidWorks Simulation Report]

Parameter	Definition
Mesh Type	Solid Mesh
Mesher Used	Blended curvature-based mesh
Jacobian Points	4 points
Maximum Element Size	1.2 mm
Minimum Element Size	1.2 mm
Mesh Quality Plot	High
Total Nodes	256456
Total Elements	161720

Table 4.3: 4.5 Beam Mesh information [SolidWorks Simulation Report]

Parameter	Definition
Mesh Type	Solid Mesh
Mesher Used	Blended curvature-based mesh
Jacobian Points	4 points
Maximum Element Size	1.2 mm
Minimum Element Size	1.2 mm
Mesh Quality Plot	High
Total Nodes	155463
Total Elements	96890

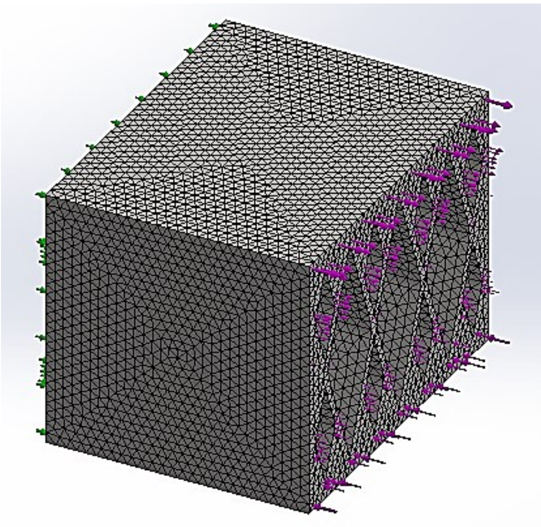


Figure 4.4: 4.5 Beam Model Simulation Fixtures, Gradient Pressure and Mesh [SolidWorks Simulation]

4.3 Experiments

The experiments were performed in the Laboratory for Machine Elements and Laboratory for Design Evaluations of the Faculty of Mechanical Engineering of Ljubljana. MTS Landmark 370.10 was used for the Compression Test and MTS Landmark 370.02 for the Bending Test.

All specimens were tested to failure, pressing at constant speed, 1 mm/min, measuring the load, force applied, and displacement. The graphs obtained show Load versus Extension or Displacement.

4.3.1 Compression Test Experiment

The main goal of these compression tests was to determine the anisotropy effect on the mechanical properties of the three types of specimens. In total, nine specimens were used, three of each type:

- Specimens and Test Runs 1, 2, 3: Brick 3.3.2 built in X direction.
- Specimens and Test Runs 4, 5, 6: Brick 3.3.2 built in Y direction.
- Specimens and Test Runs 7, 8, 9: Brick 4.5 built in Y direction.

Figure 4.5: Compression Test for specimens 1, 4 and 7 (Left to right).

4.3.2 Bending Test Experiment

The main goal of these Bending Tests was to compare the mechanical performance of beams 3.2.2 and 4.5 and compare the experimental results with the simulation results. In total 4 specimens were used, 2 of each type:

- Specimens and Test Runs 1, 2: Beam 4.5 built in Y direction.
- Specimens and Test Runs 3, 4: Beam 3.2.2 built in Y direction.

At first, the specimens were supported at the end or edges of the beam. However, they could not resist the local pressure and were smashed, being the different layers separated due to lack of cohesion between layers. Then, it was decided that the lower supports would be placed 30 mm away from the end of beam. This means that the centres of the supports were placed at: 35 mm (Left support), 90 mm (Load) and 145 mm (Right support).

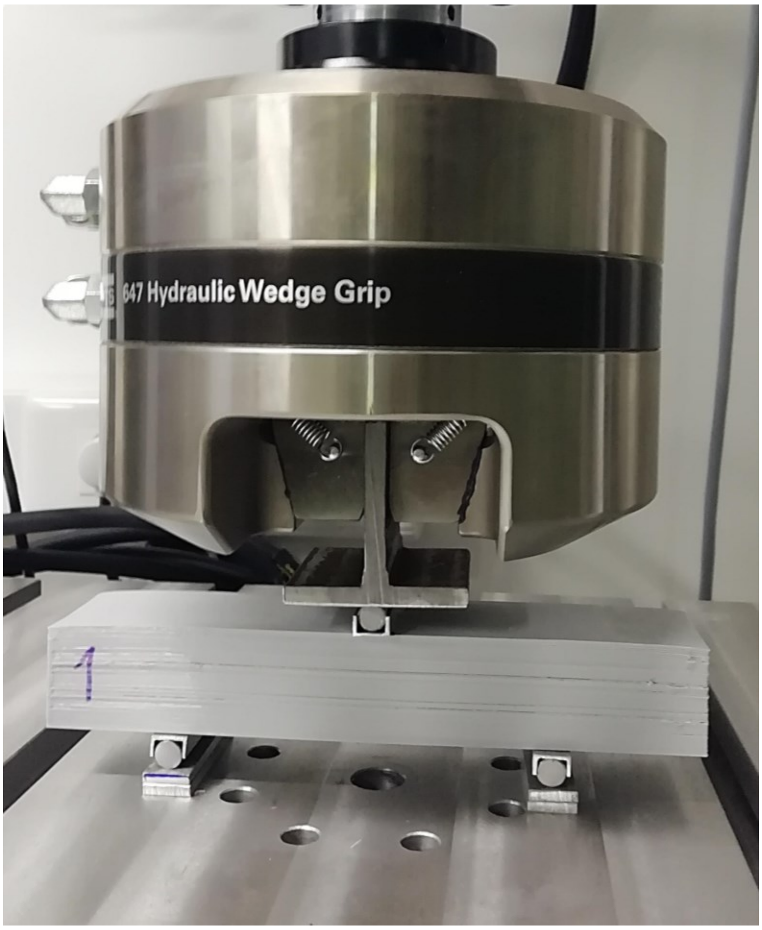
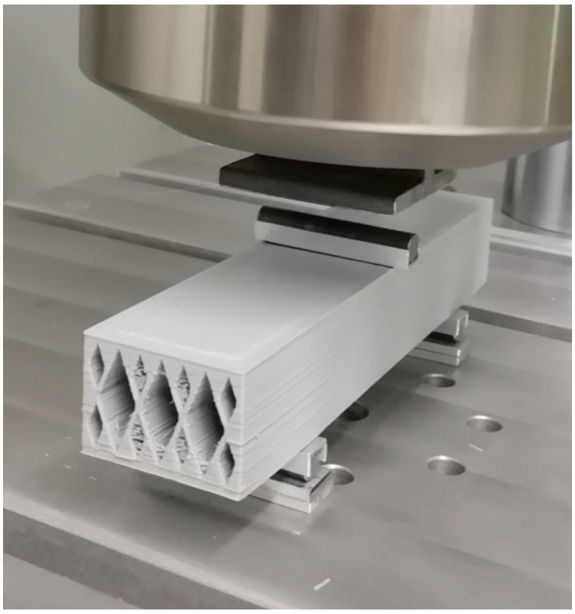


Figure 4.6: Bending Test for specimen 1



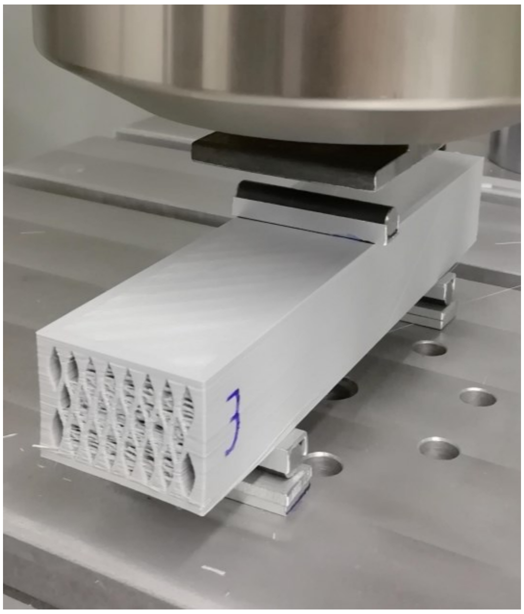


Figure 4.7: Specimen 2. Beam 4.5

Figure 4.8: Specimen 3. Beam 3.2.2

4.4 Tensile Test Experiment

The main goal of these extra tensile tests was to determine the temperature effect on the mechanical properties of the PLA thermoplastic material after testing one beam at high temperature and realising it performed a lot worse. In total, four tensile specimens were used.

The tensile specimens' dimensions were:
- Width: 12 mm
- Thickness: 3 mm
- Area: 36 mm^2
- Length: 25 mm

The exact dimensions of the specimens varied because of FDM technology tolerances. However, the exact dimensions were measured and used to calculate properly the real Stress (MPa) and Elongation (%).

5 Results and Discussion

5.1 Simulation

5.1.1 Compression Test Simulation

The results of the 3.2.2 model simulation compression test in the X, Y and Z axes are: Displacement (URES), von Mises Stress, 1st Principal Stress (P1), 3rd Principal Stress (P3), X Normal Stress (SX), Y Normal Stress (SY) and Z Normal Stress (SZ).

As it was said before, the objective of this simulation is to decide which would be the best direction to perform the compression test on the 3.2.2 model bricks.

5.1.1.1 X axis

Performing the compression test in the X axis is not a really interesting way of testing the bricks. In this case, the pressure would be applied in the direction of the profile. This means that the area would be constant and the test would give similar results for different shapes, if they have the same area.

Compression test in the X axis simulation images are shown next.

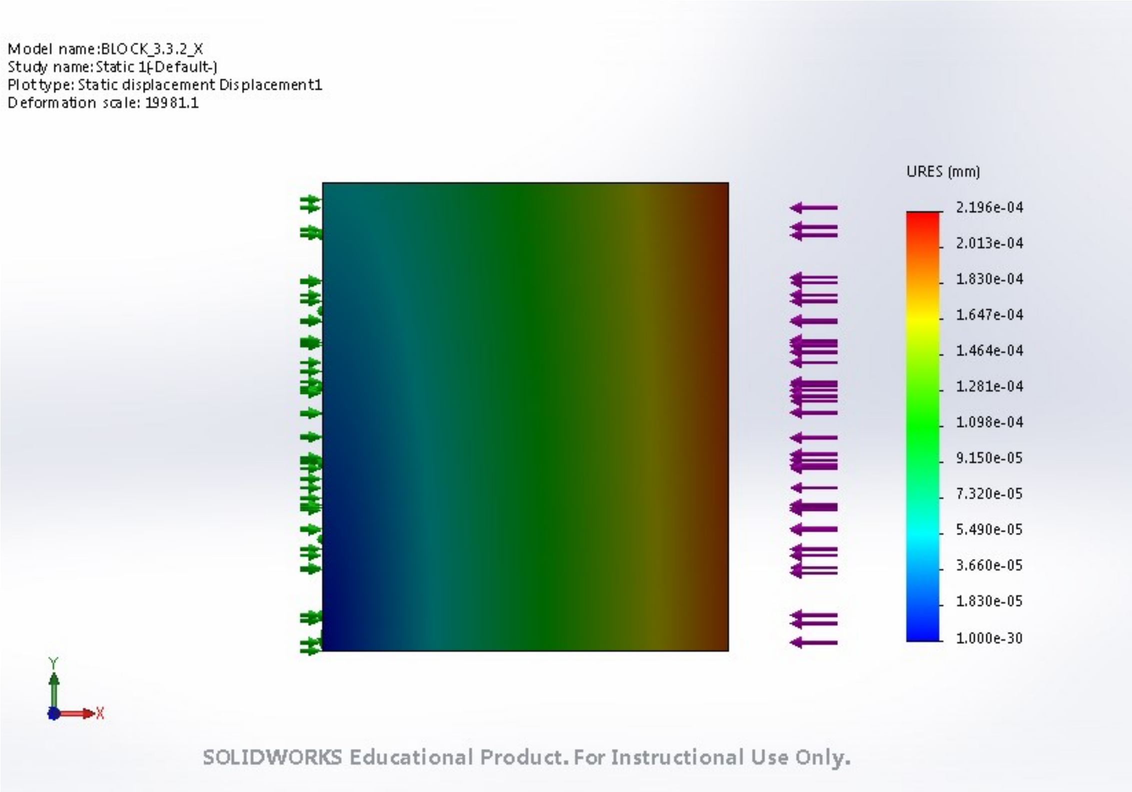


Figure 5.1: :3.3.2 Model X axis Displacement Result [SolidWorks]

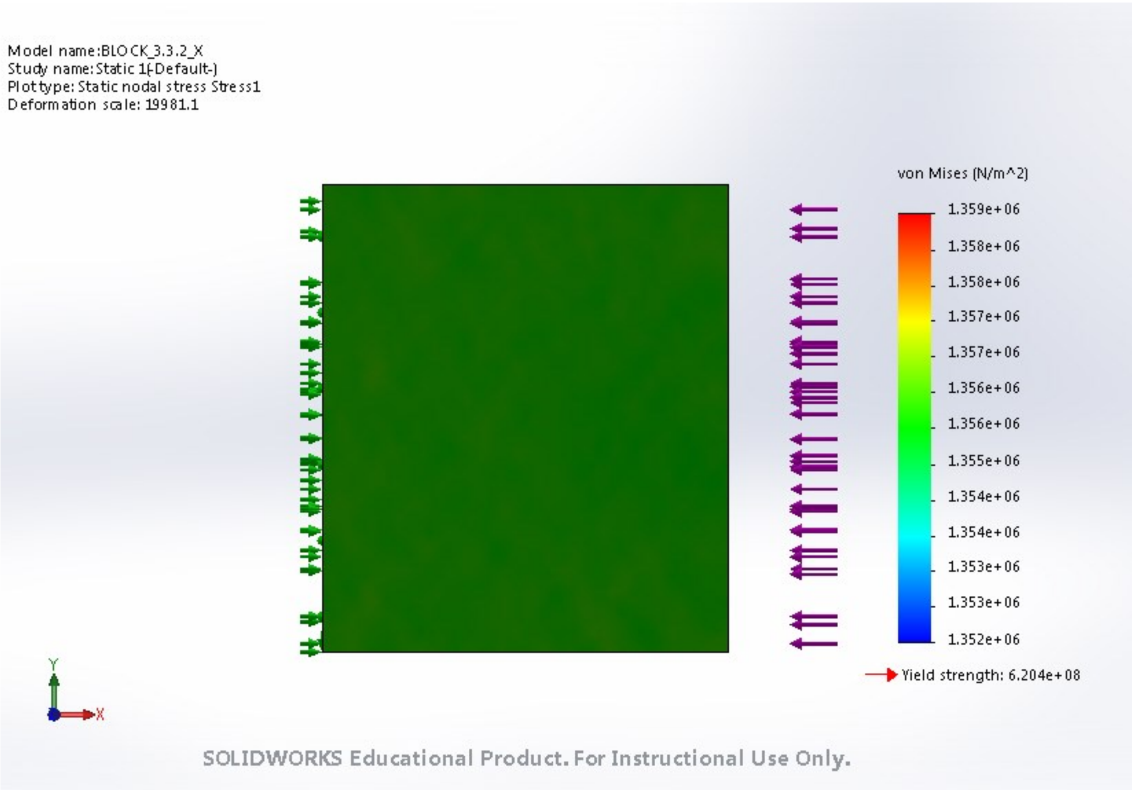


Figure 5.2: 3.3.2 Model X axis von Mises Stress Result [SolidWorks]

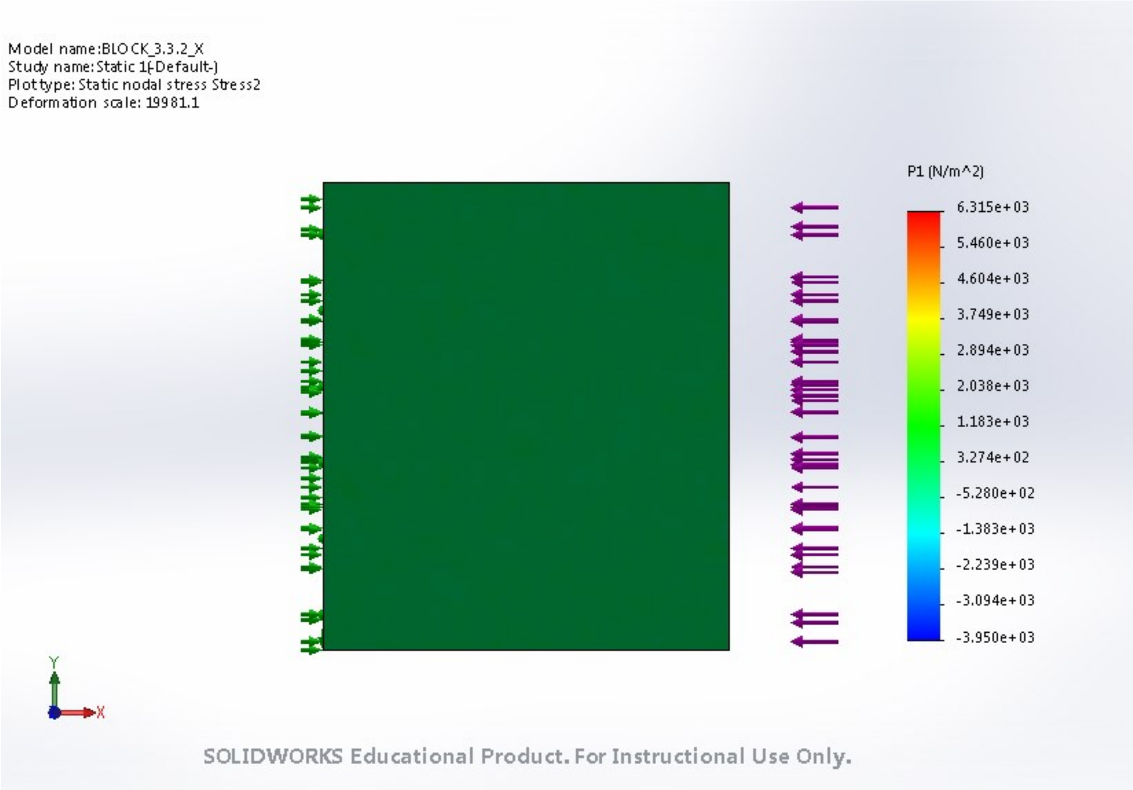


Figure 5.3: 3.3.2 Model X axis 1st Principal Stress Result [SolidWorks]

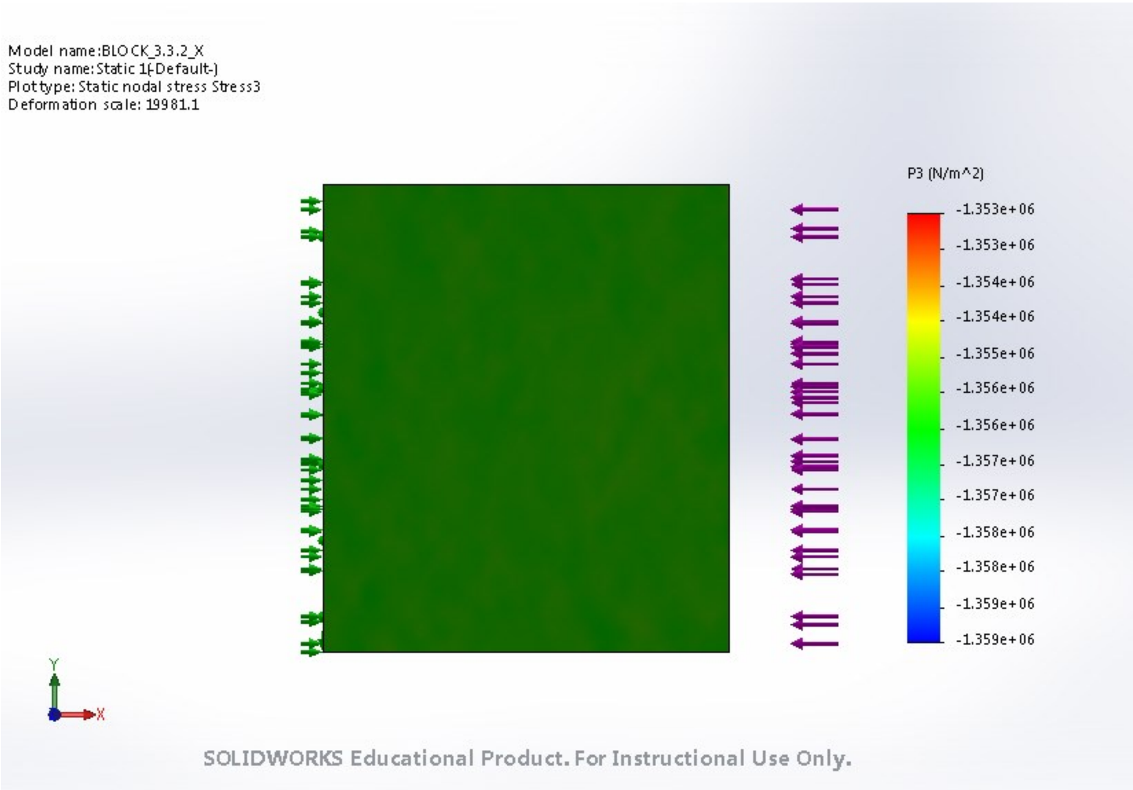


Figure 5.4: 3.3.2 Model X axis 3rd Principal Stress Result [SolidWorks]

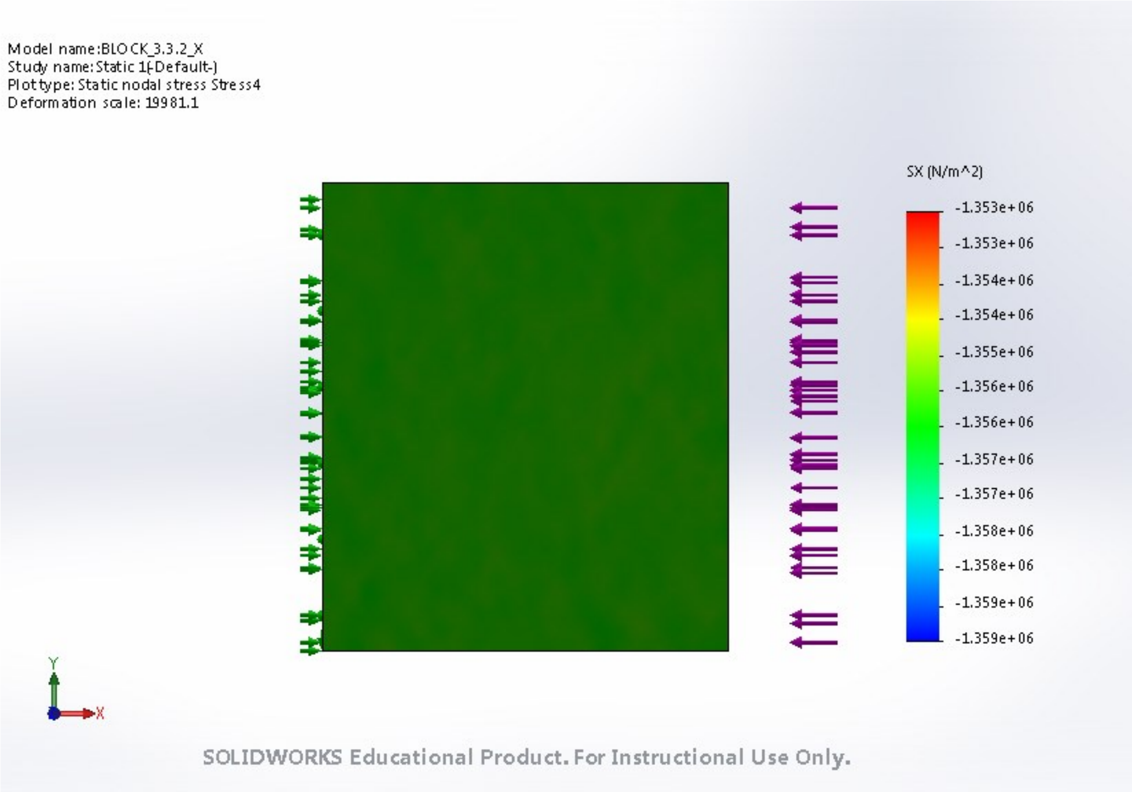


Figure 5.5: 3.3.2 Model X axis X Normal Stress Result [SolidWorks]

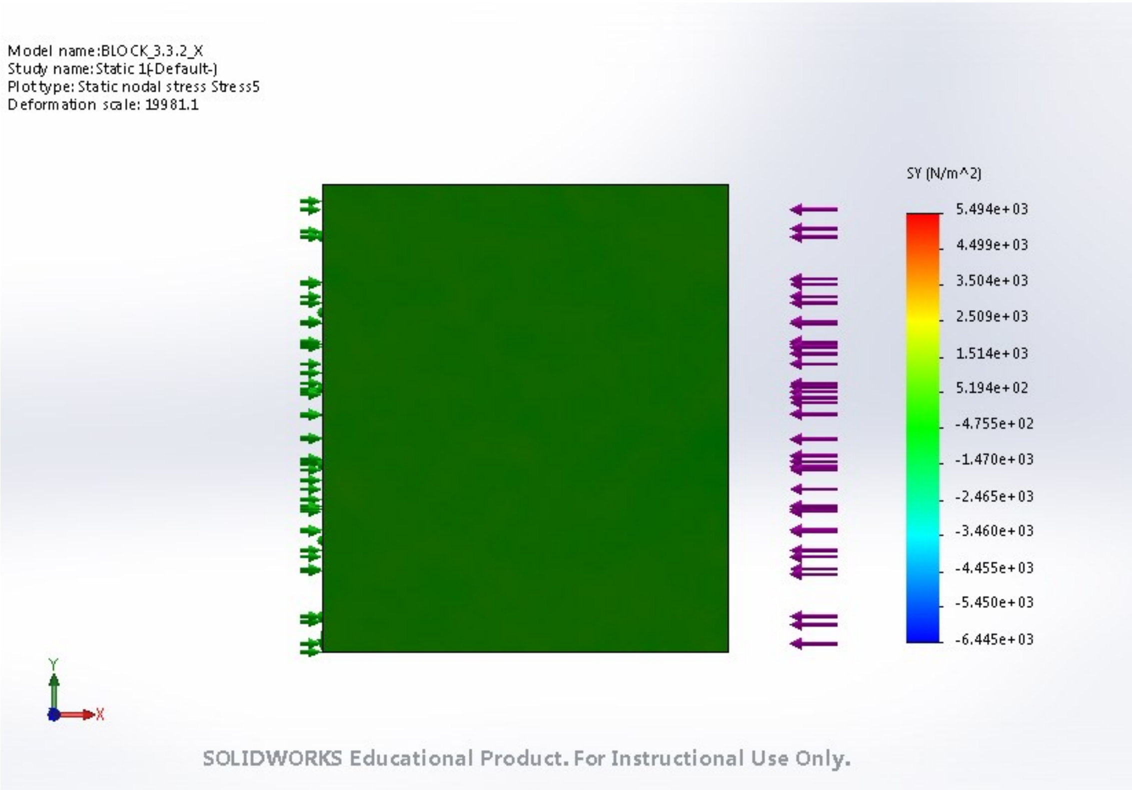


Figure 5.6: 3.3.2 Model X axis Y Normal Stress Result [SolidWorks]

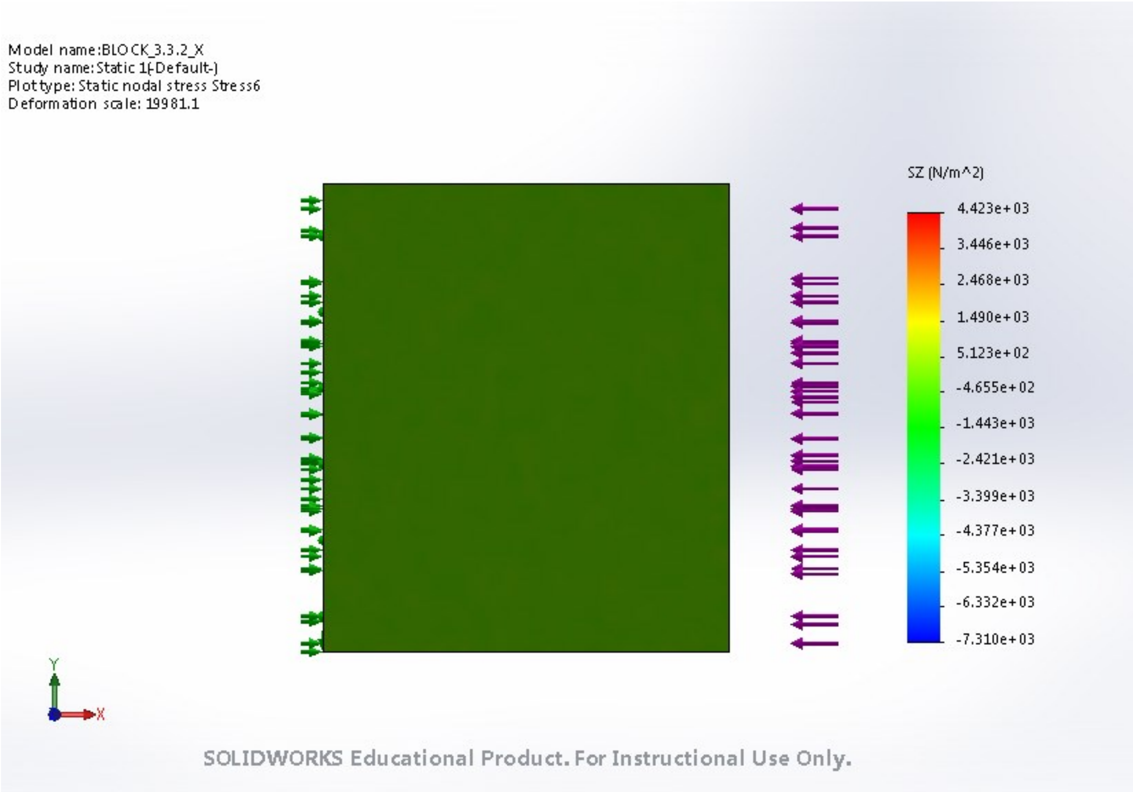


Figure 5.7: 3.3.2 Model X axis Z Normal Stress Result [SolidWorks]

After seeing the simulation results it is clear that this is not the best way of testing the bricks because it does not really test the internal structure. However, it would give interesting results if the bricks are printed in different directions.

5.1.1.2 Y axis

Performing the compression test in the Y axis is the best way of testing the internal structure while studying anisotropy of the material. If the pressure is applied in the Y axis, the internal structure and the edges tend to buckle and the stresses are distributed quite uniformly along all the structure.

The results of the displacement simulation are not symmetric because of boundary conditions, only two edges and the bottom surface are fixed. Refined meshing might homogenize the results.

It can be seen that the sharp edges of the internal structure concentrate stress bit but it is not critical.

Compression test in the Y axis simulation images are shown next.

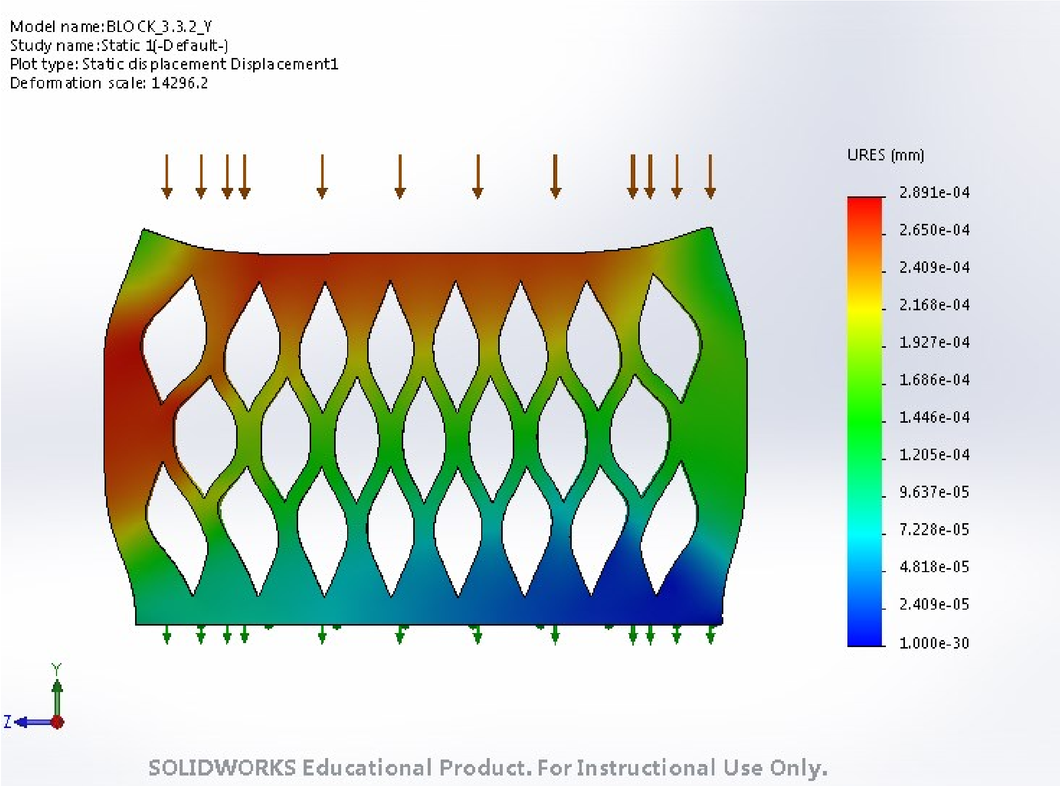


Figure 5.8: 3.3.2 Model Y axis Displacement Result [SolidWorks]

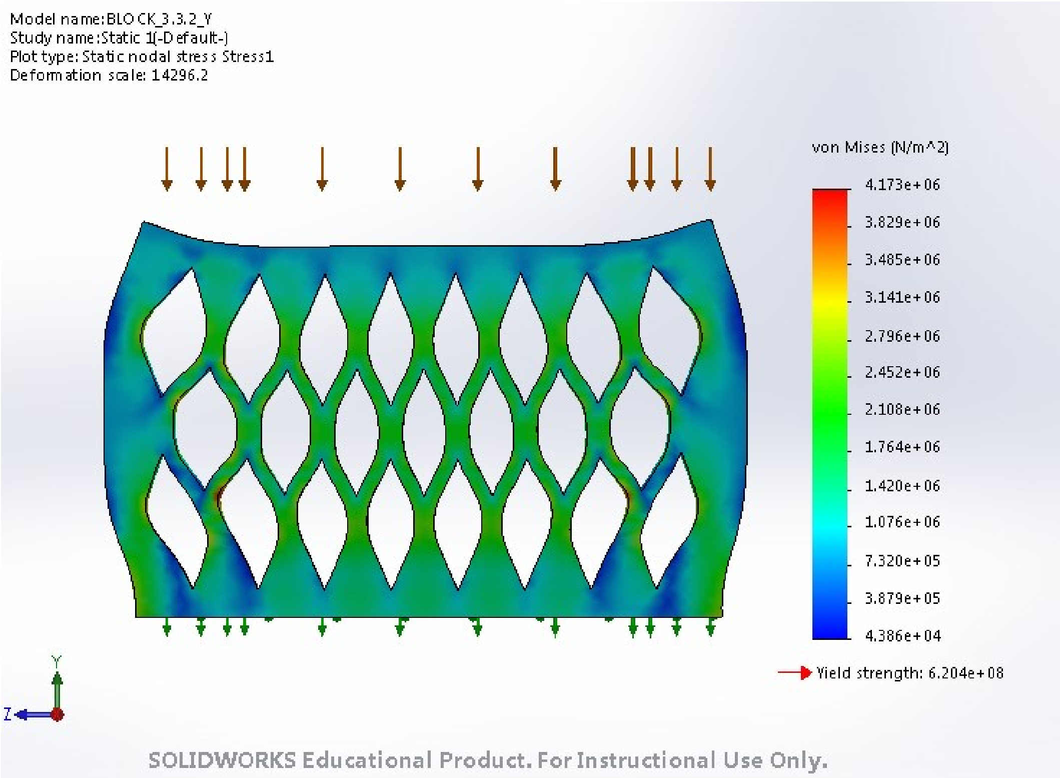


Figure 5.9: 3.3.2 Model Y axis von Mises Stress Result [SolidWorks]

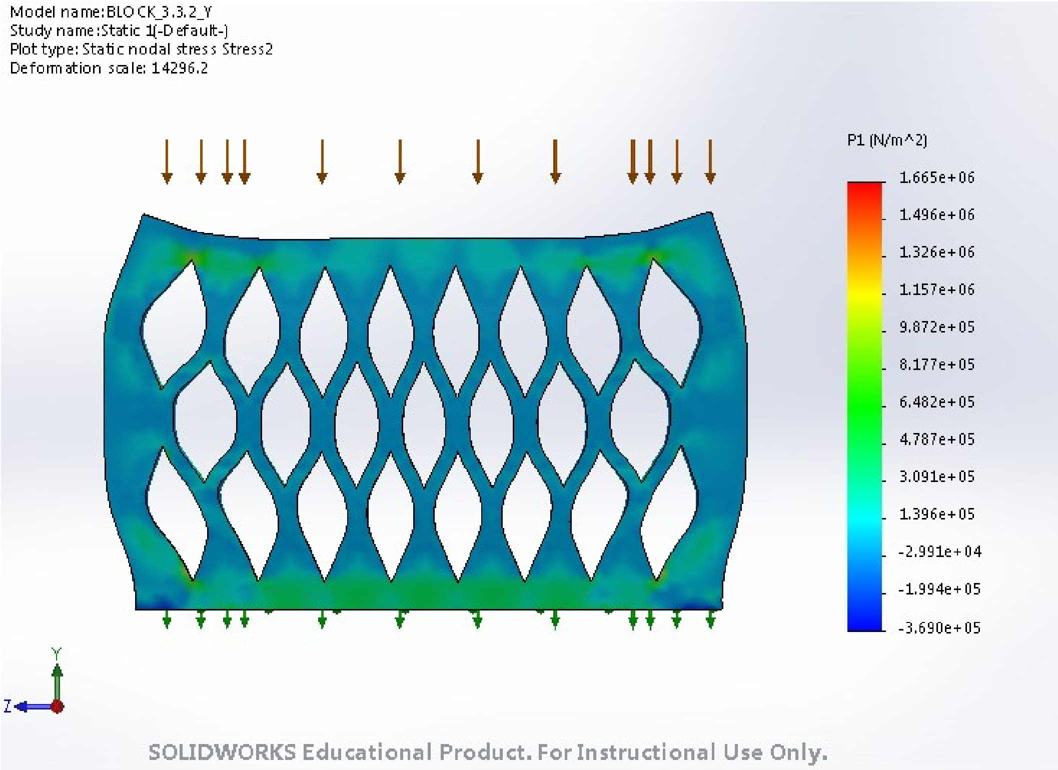


Figure 5.10: 3.3.2 Model Y axis 1st Principal Stress Result [SolidWorks]

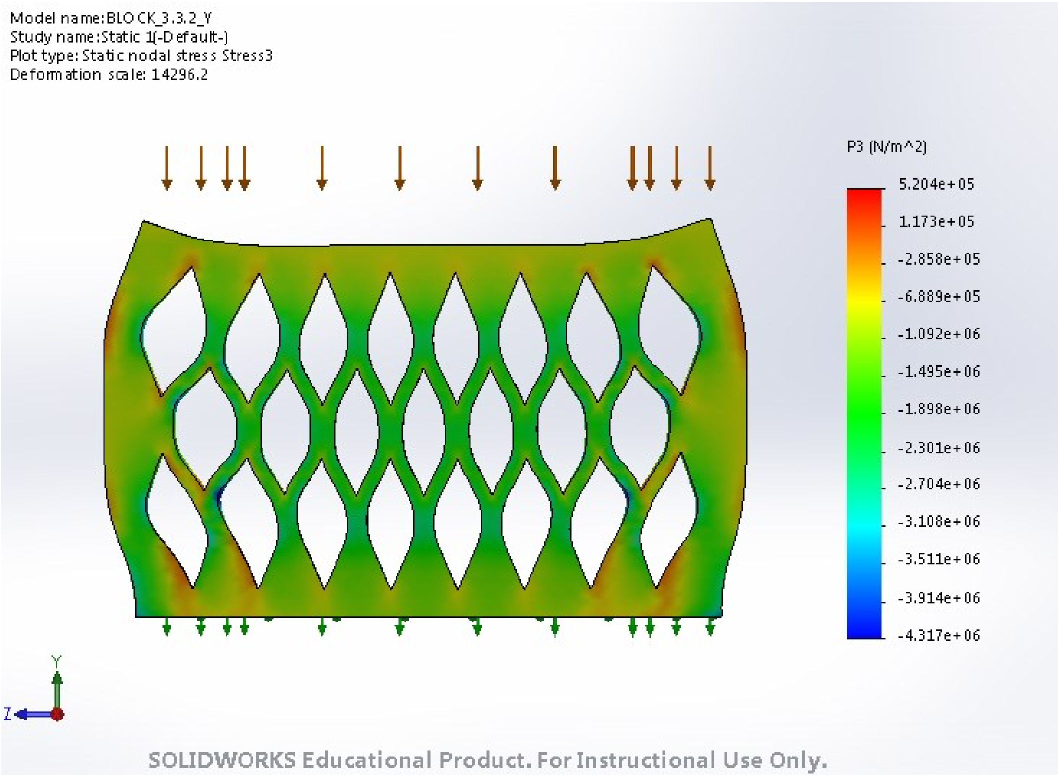


Figure 5.11: 3.3.2 Model Y axis 3rd Principal Stress Result [SolidWorks]

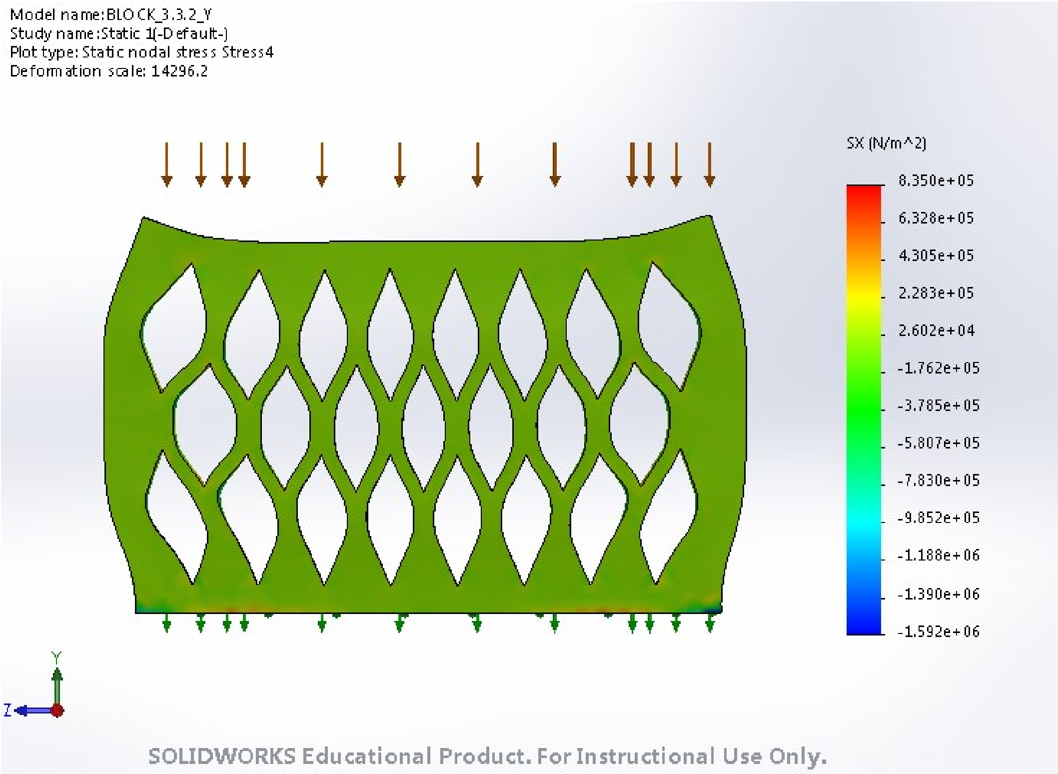


Figure 5.12: 3.3.2 Model Y axis X Normal Stress Result [SolidWorks]

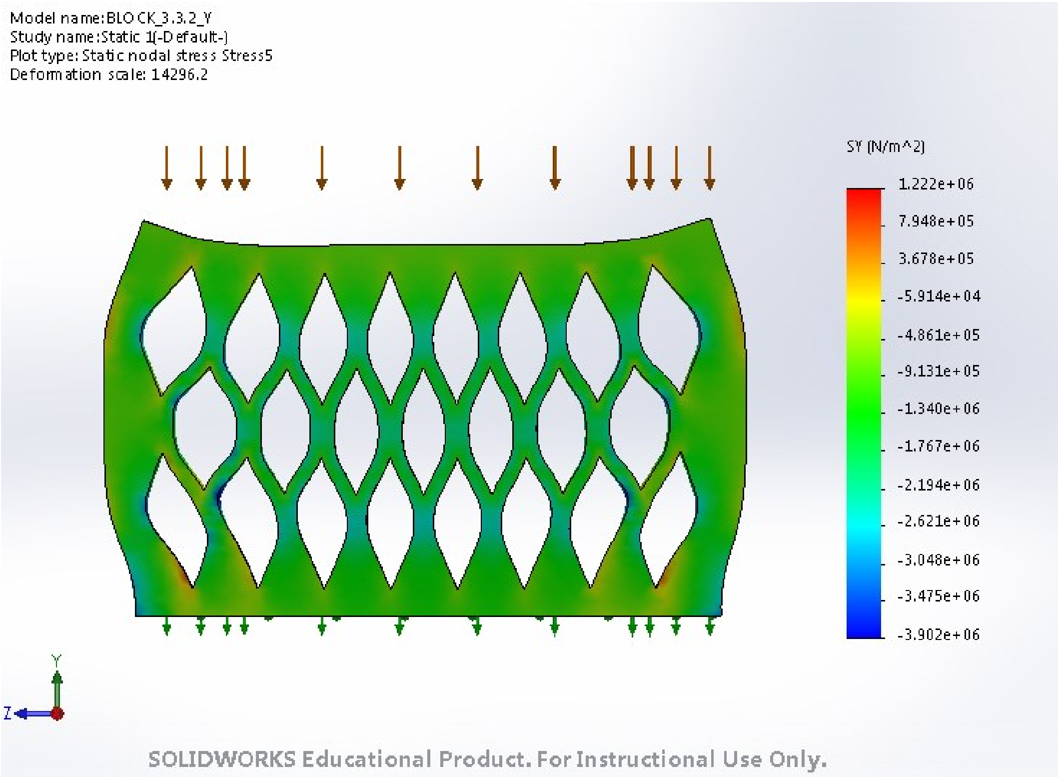


Figure 5.13: 3.3.2 Model Y axis Y Normal Stress Result [SolidWorks]

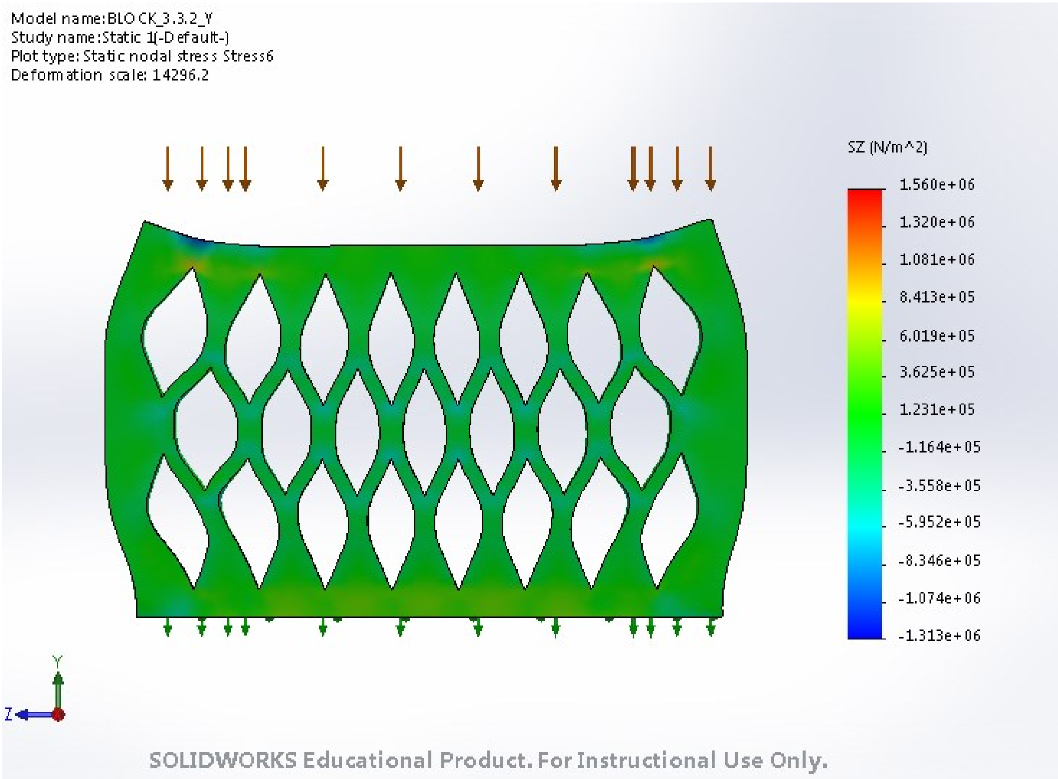


Figure 5.14: 3.3.2 Model Y axis Z Normal Stress Result [SolidWorks]

After seeing the simulation results it can be said that testing in the Y direction could be interesting to test the internal structure. In addition, the load applied in the bending test will be applied in the same direction and position.

5.1.1.3 Z axis

Performing the compression test in the Z axis is the worst way of testing the bricks. In this case, the pressure would break, deform and smash the internal structure which is not designed to work in this direction.

It can be seen how the pressing machine would be smashing the internal structure step by step, not pressing the whole brick structure. The stresses are not placed uniformly.

Compression test in the Z axis simulation images are shown next.

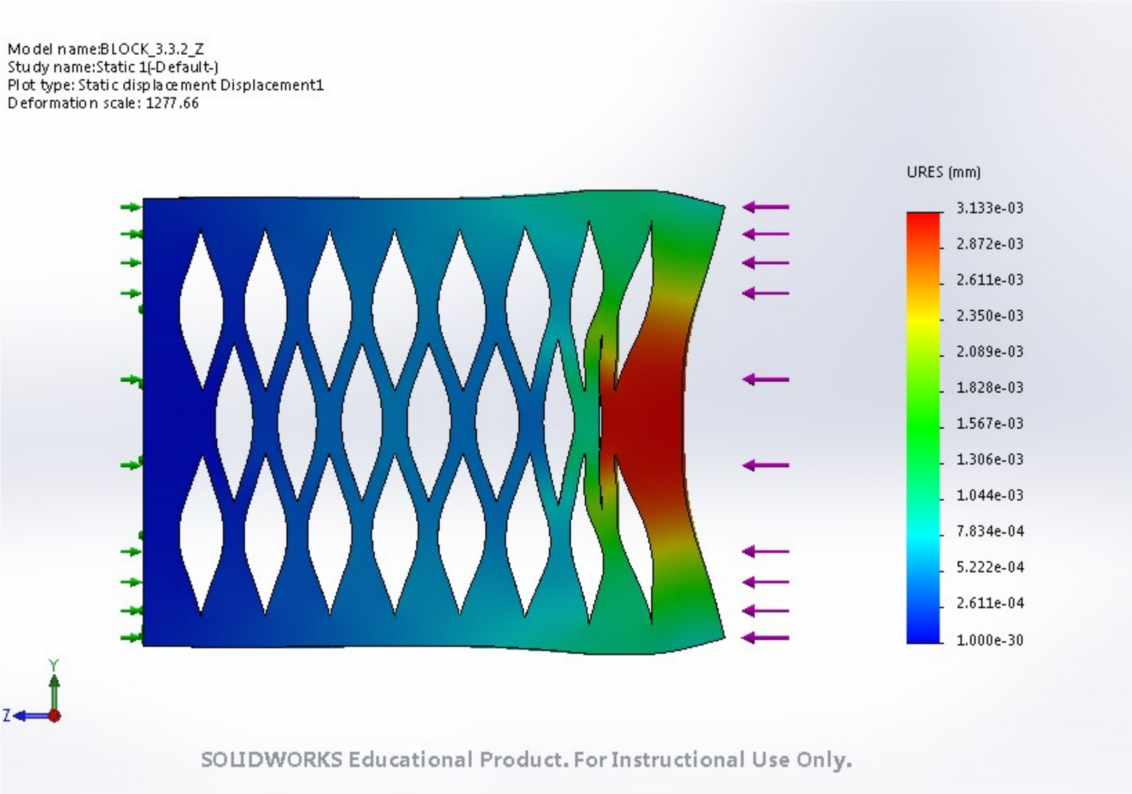


Figure 5.15: 3.3.2 Model Z axis Displacement Result [SolidWorks]

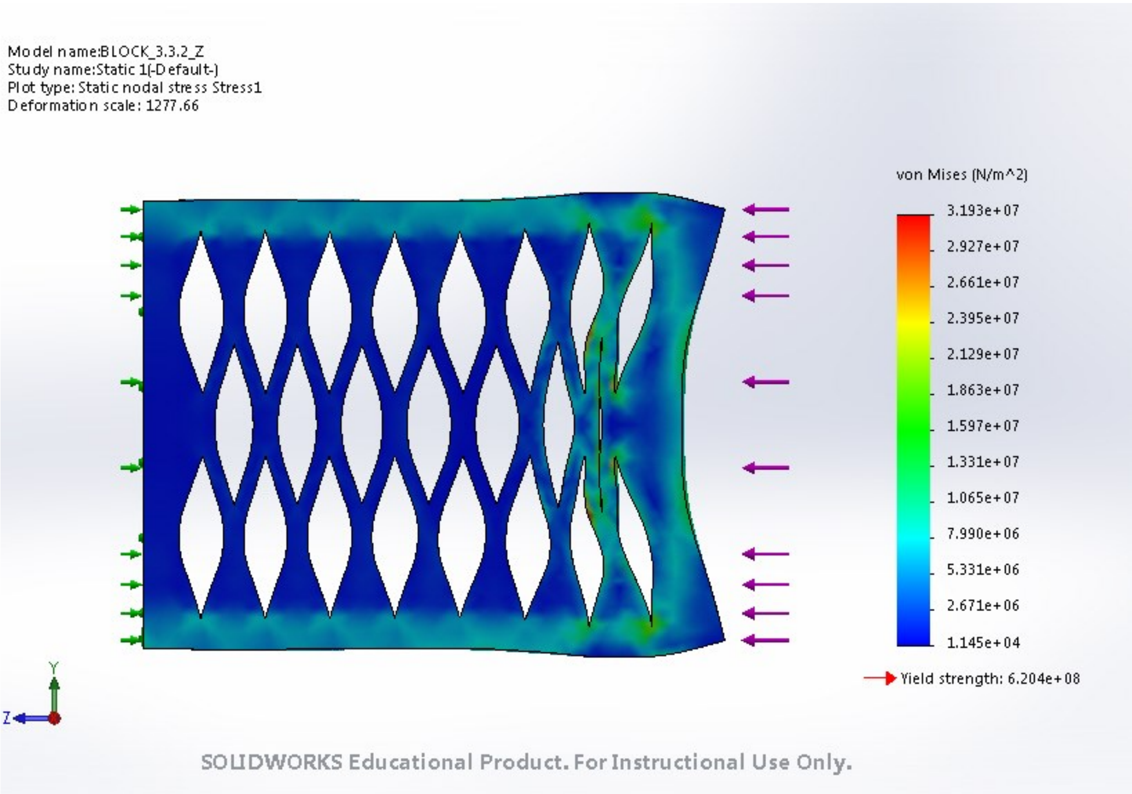


Figure 5.16: 3.3.2 Model Z axis von Mises Stress Result [SolidWorks]

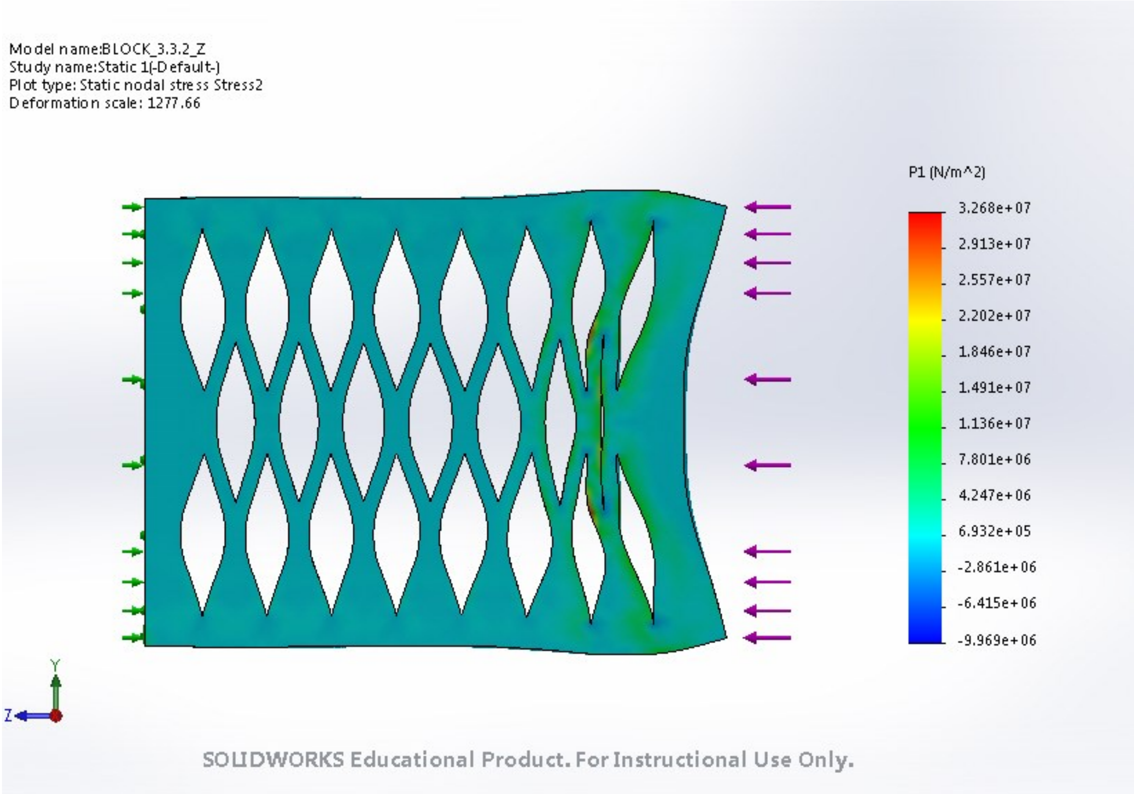


Figure 5.17: 3.3.2 Model Z axis 1st Principal Stress Result [SolidWorks]

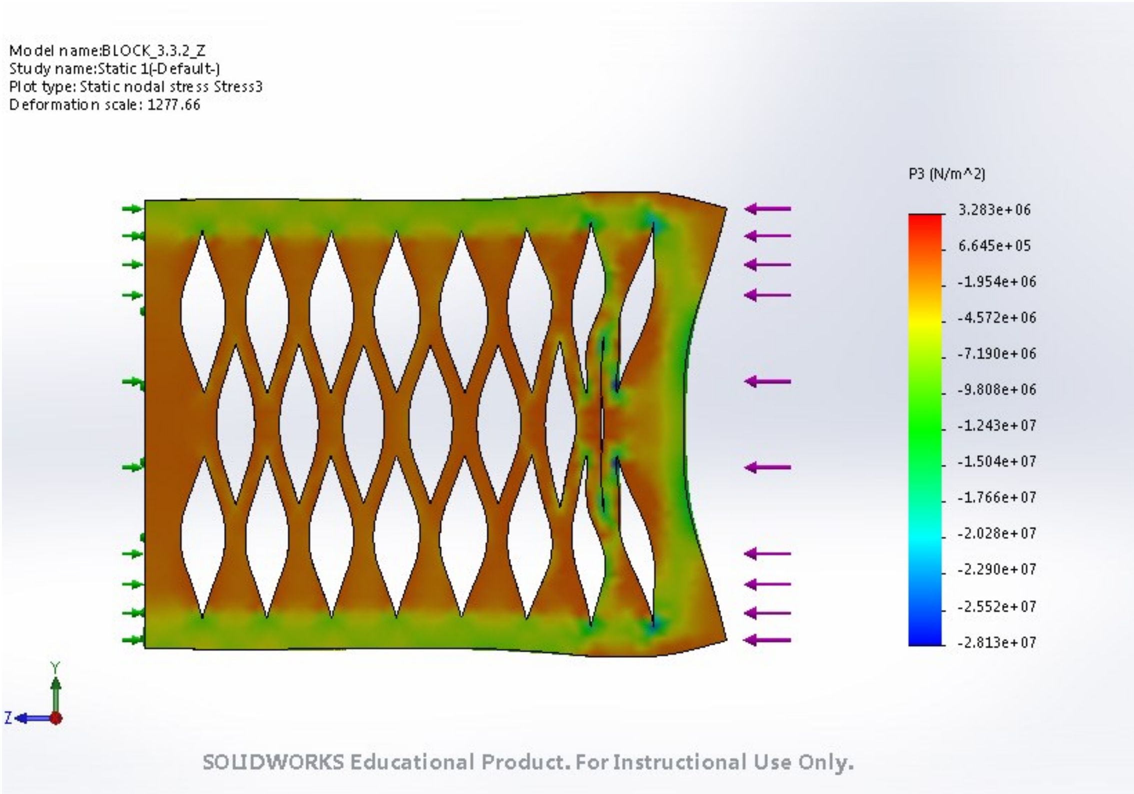


Figure 5.18: 3.3.2 Model Z axis 3rd Principal Stress Result [SolidWorks]

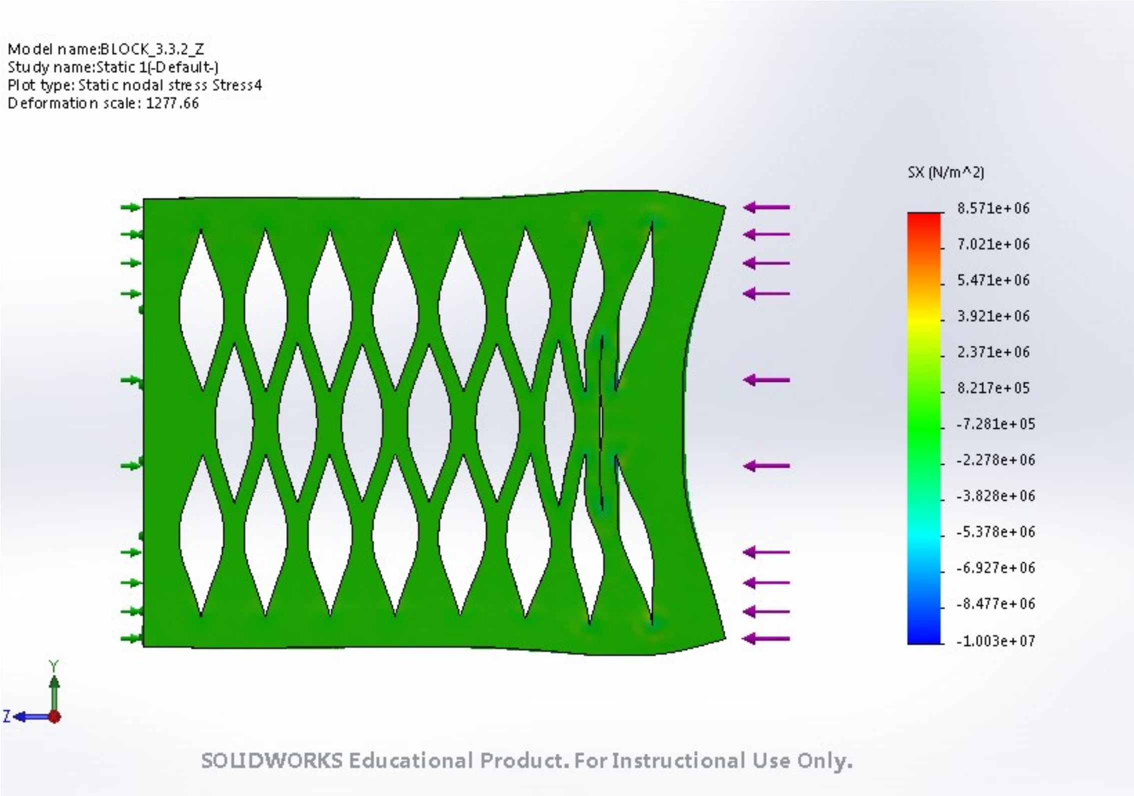


Figure 5.19: 3.3.2 Model Z axis X Normal Stress Result [SolidWorks]

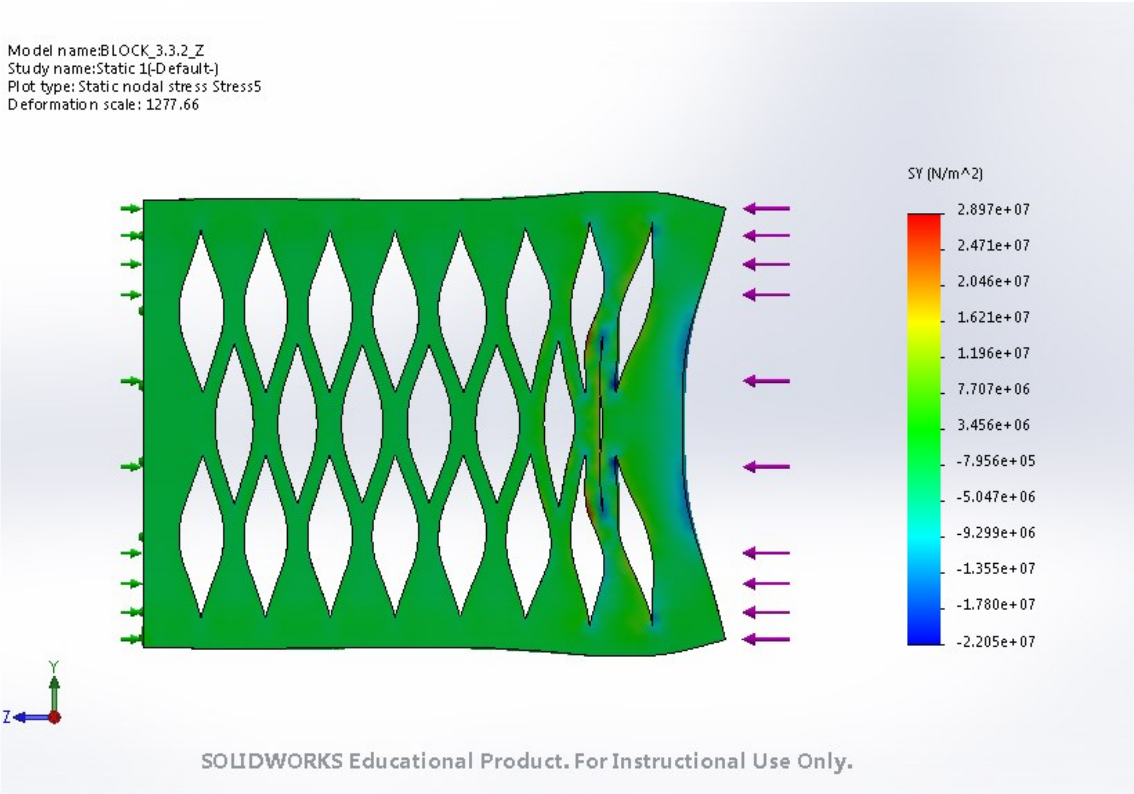


Figure 5.20: 3.3.2 Model Z axis Y Normal Stress Result [SolidWorks]

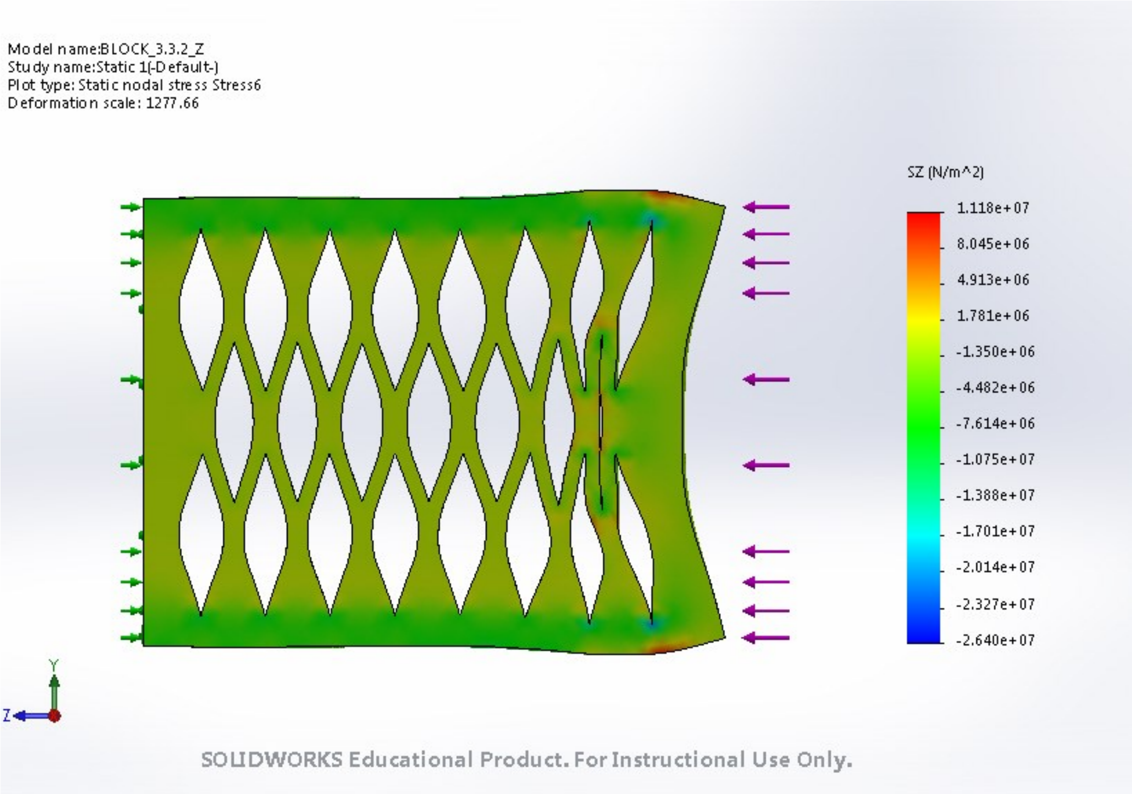


Figure 5.21: 3.3.2 Model Z axis Z Normal Stress Result [SolidWorks]

5.1.2 Bending Test Simulation

The results of the 3.2.2 and 4.5 models bending tests simulations are: Displacement (URES), Strain Result (ESTRN), von Mises Stress, 1st Principal Stress (P1), 3rd Principal Stress (P3), X Normal Stress (SX), Y Normal Stress (SY) and Z Normal Stress (SZ).

Both simulations are plotted with the same unit dimensions and colour range to make it easier to appreciate the differences. Moreover, in the chapter 5.1.2.3, there is a numerical comparison between the two models.

The main objective of this chapter is to compare the two models, 3.2.2 and 4.5, performance subjected to bending considering that there is no anisotropy. Comparing the models without anisotropy is useful to compare the structures. After comparing the structures, the next step would be to see if they work similarly being produced using FDM and PLA thermoplastic.

5.1.2.1 Bending Beam 3.3.2

The results of the bending simulation will be discussed in chapter 5.1.2.3.

Bending test for beam 3.3.2 simulation images are shown next.

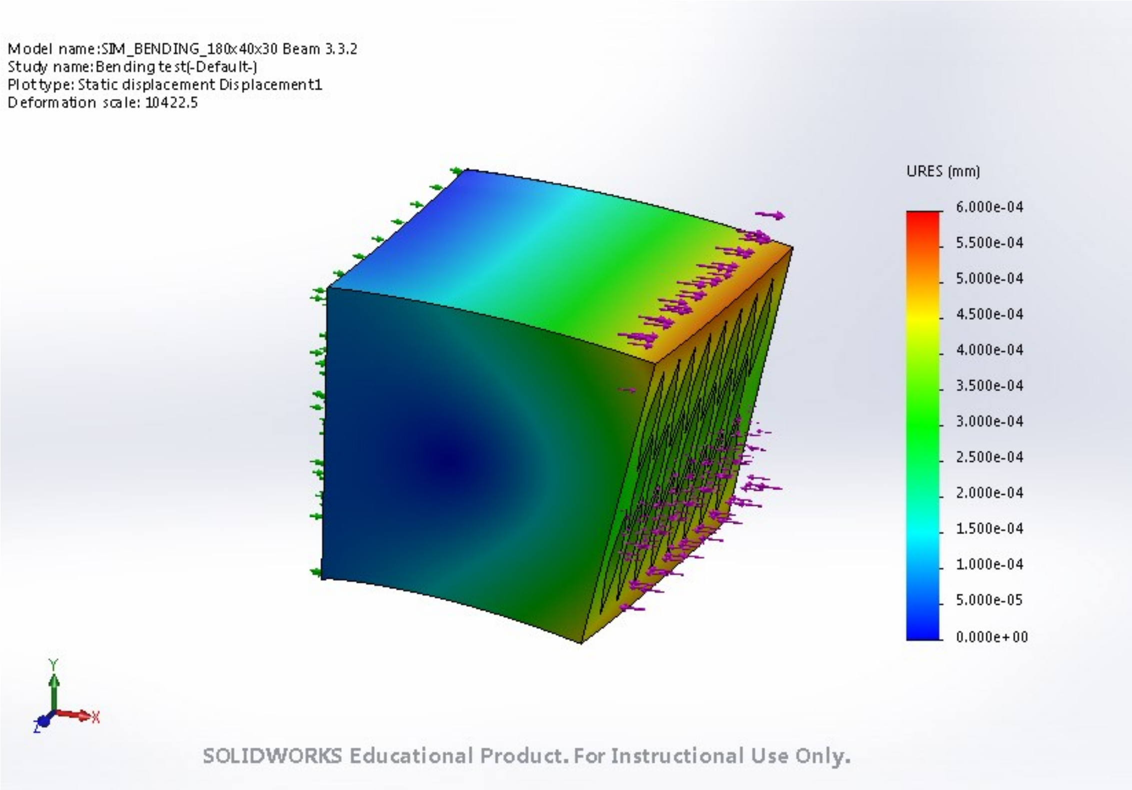


Figure 5.22: 3.3.2 Model Displacement Result [SolidWorks]

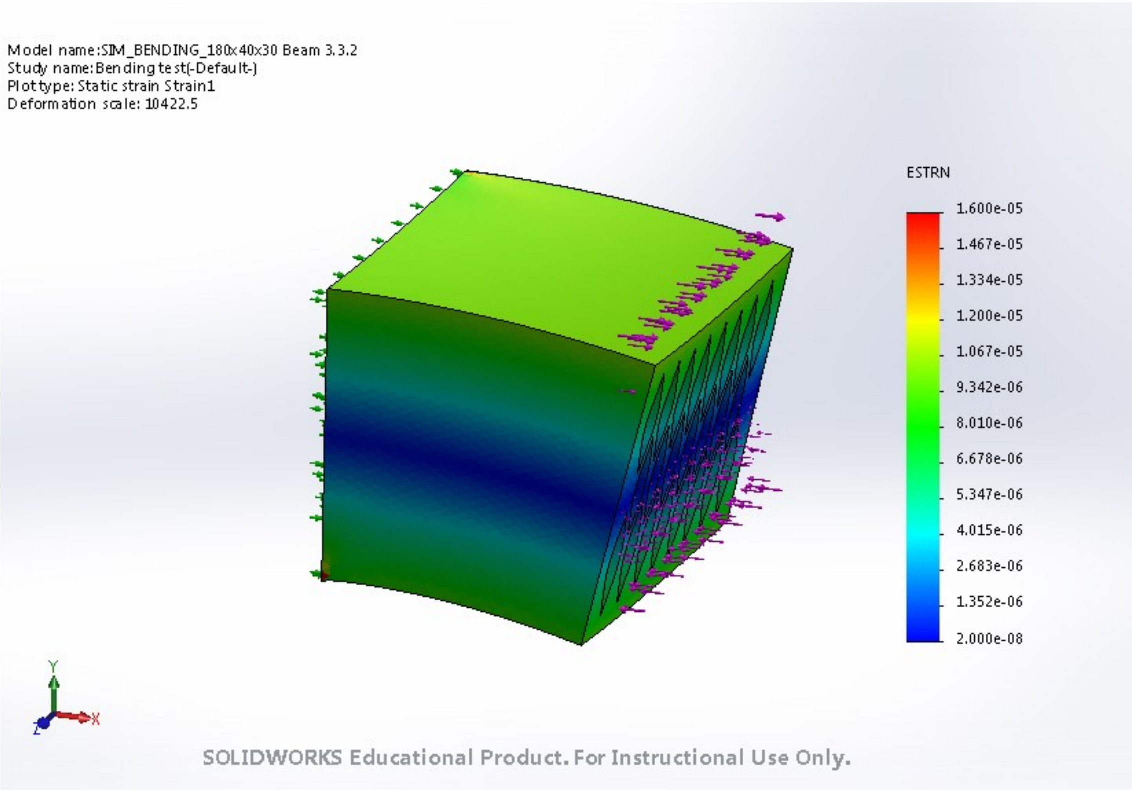


Figure 5.23: 3.3.2 Model Strain Result [SolidWorks]

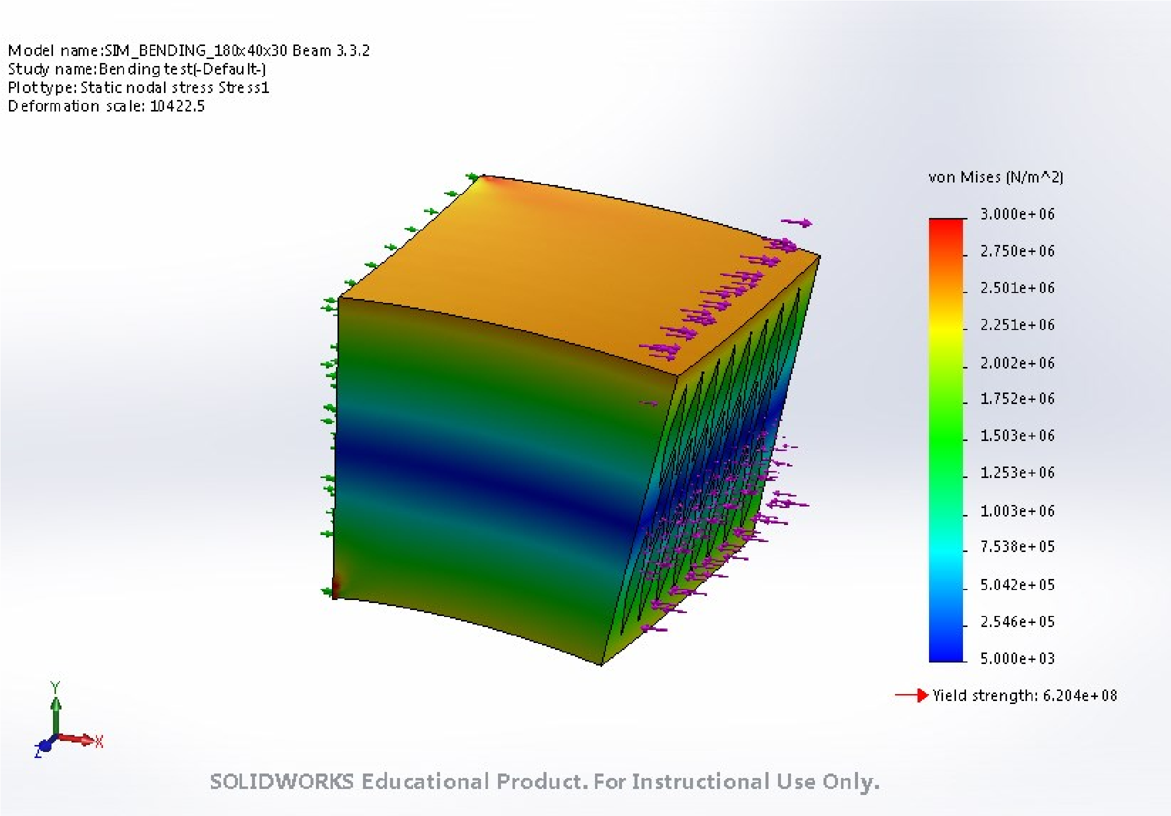


Figure 5.24: 3.3.2 Model von Mises Stress Result [SolidWorks]

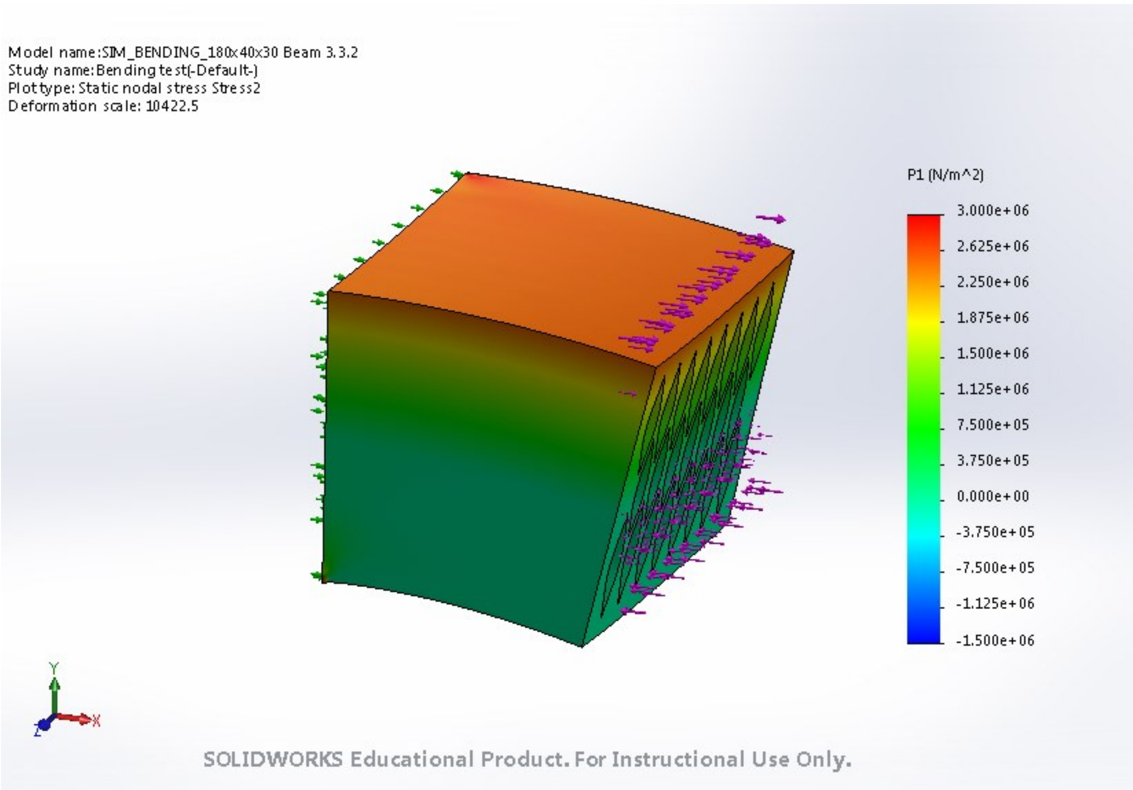


Figure 5.25: 3.3.2 Model 1st Principal Stress Result [SolidWorks]

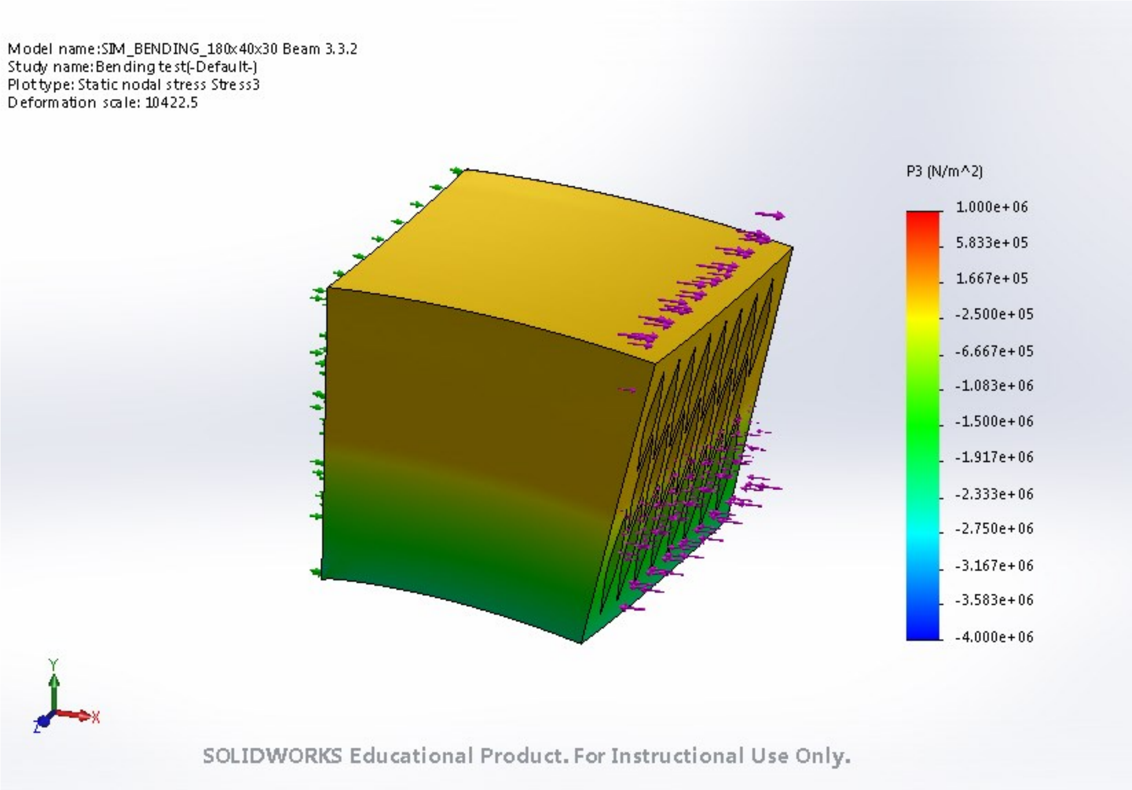


Figure 5.26: 3.3.2 Model 3rd Principal Stress Result [SolidWorks]

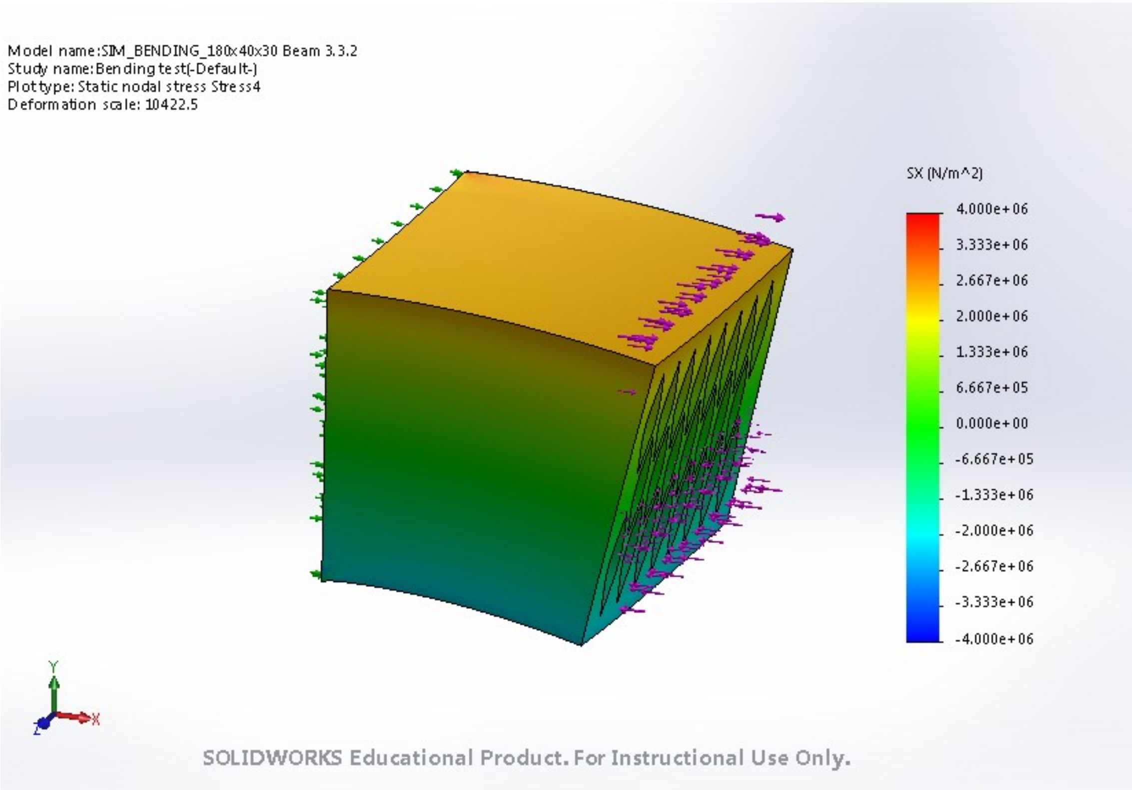


Figure 5.27: 3.3.2 Model X Normal Stress Result [SolidWorks]

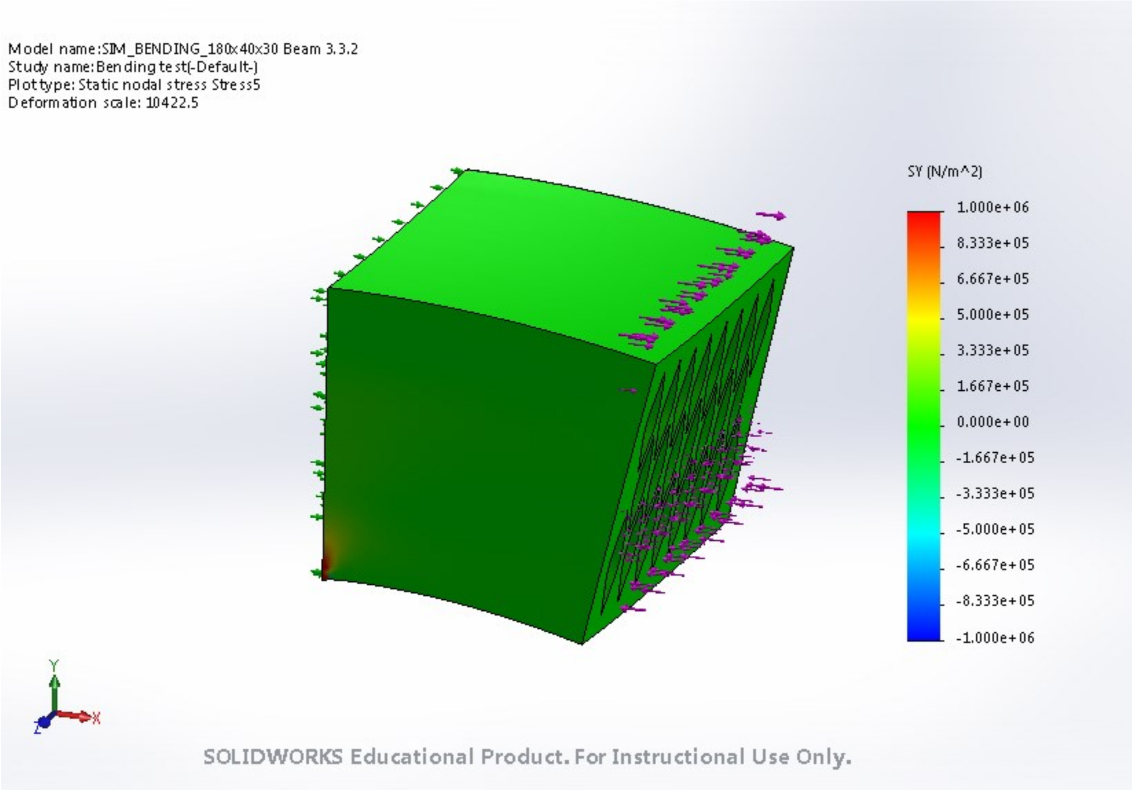


Figure 5.28: 3.3.2 Model Y Normal Stress Result [SolidWorks]

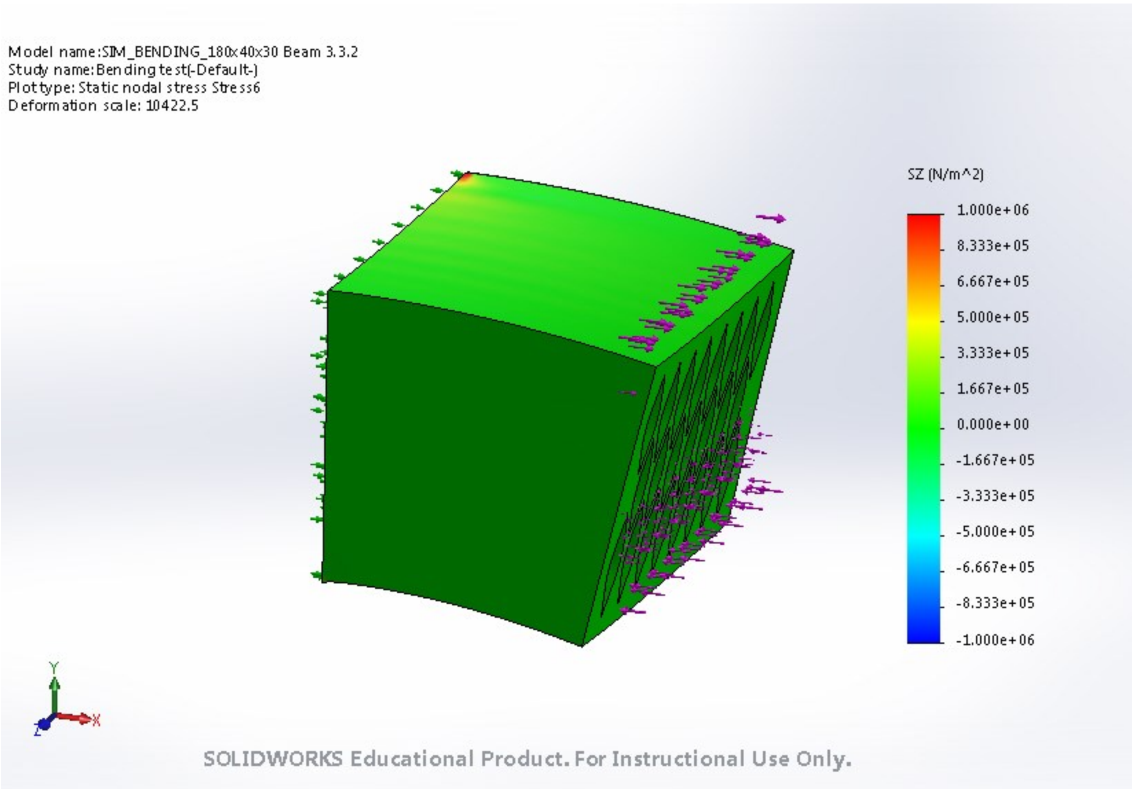


Figure 5.29: 3.3.2 Model Z Normal Stress Result [SolidWorks]

5.1.2.2 Bending Beam 4.5

The results of the bending simulation will be discussed in chapter 5.1.2.3. Bending test for beam 4.5 simulation images are shown next.

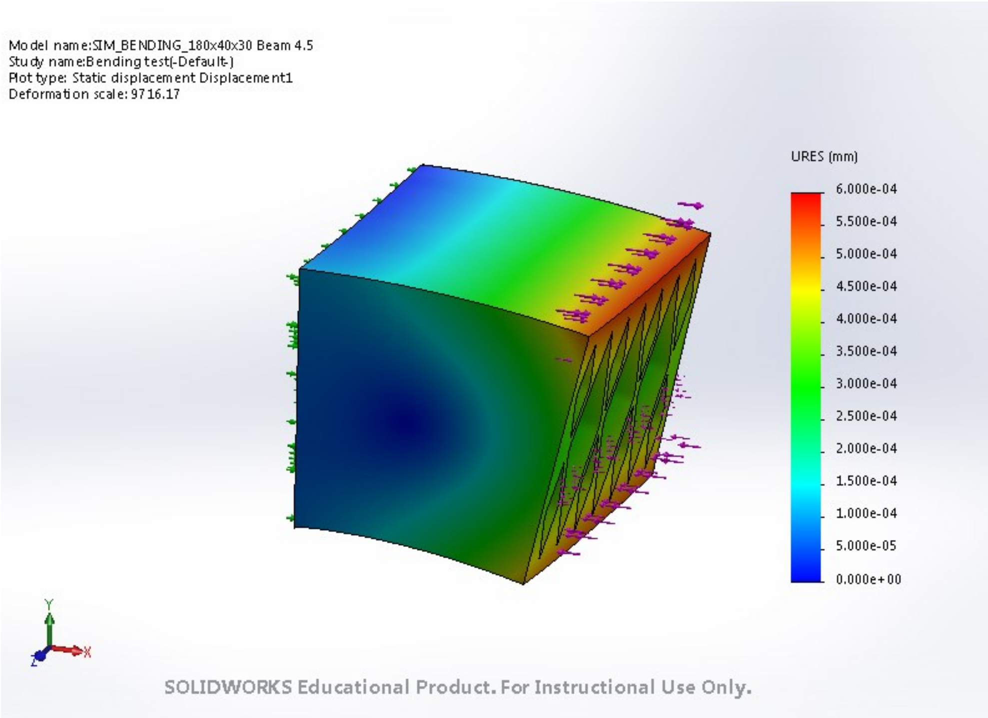


Figure 5.30: 4.5 Model Displacement Result [SolidWorks]

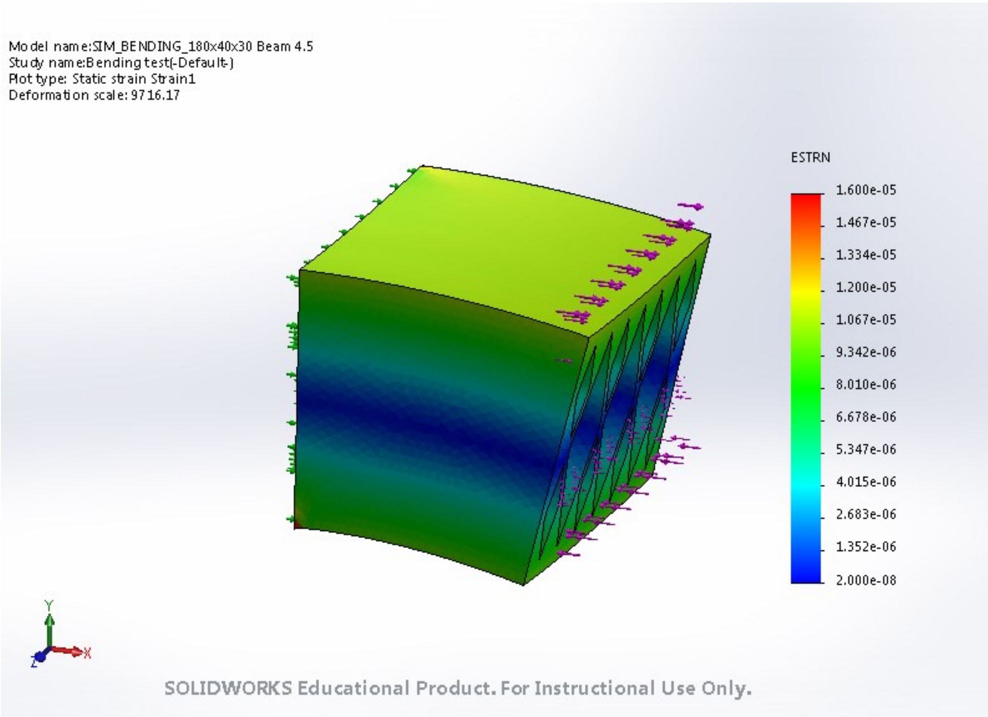


Figure 5.31: 4.5 Model Strain Result [SolidWorks]

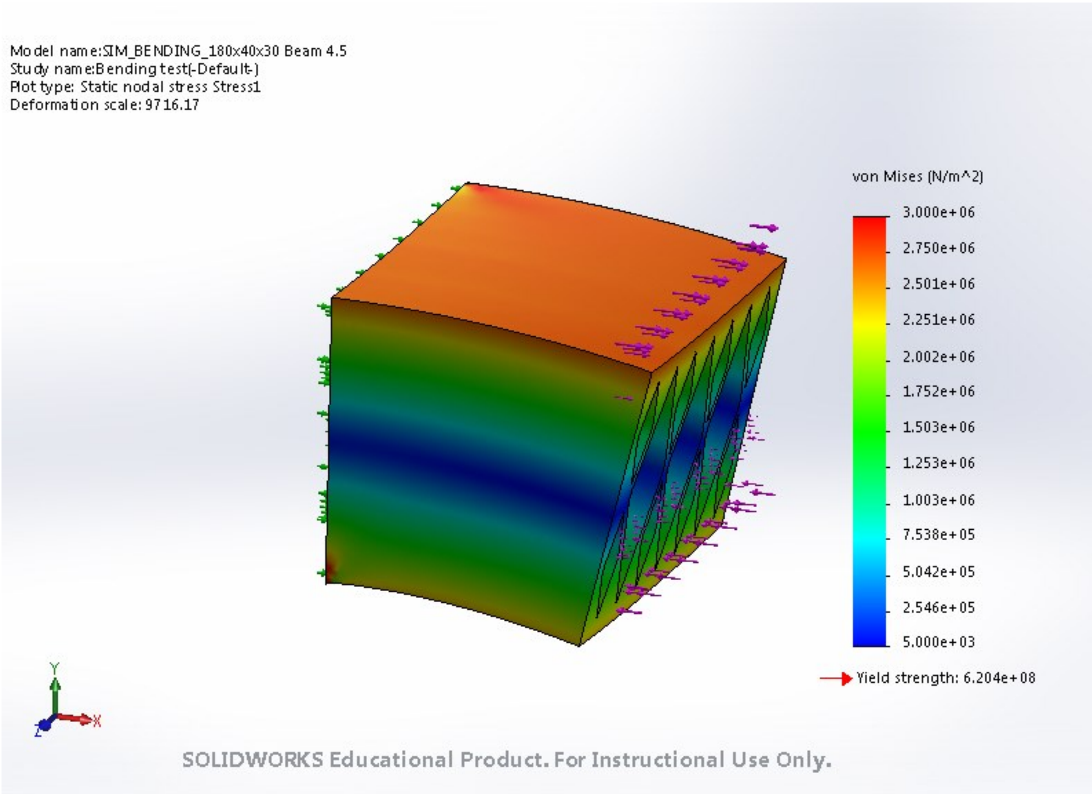


Figure 5.32: 4.5 Model von Mises Stress Result [SolidWorks]

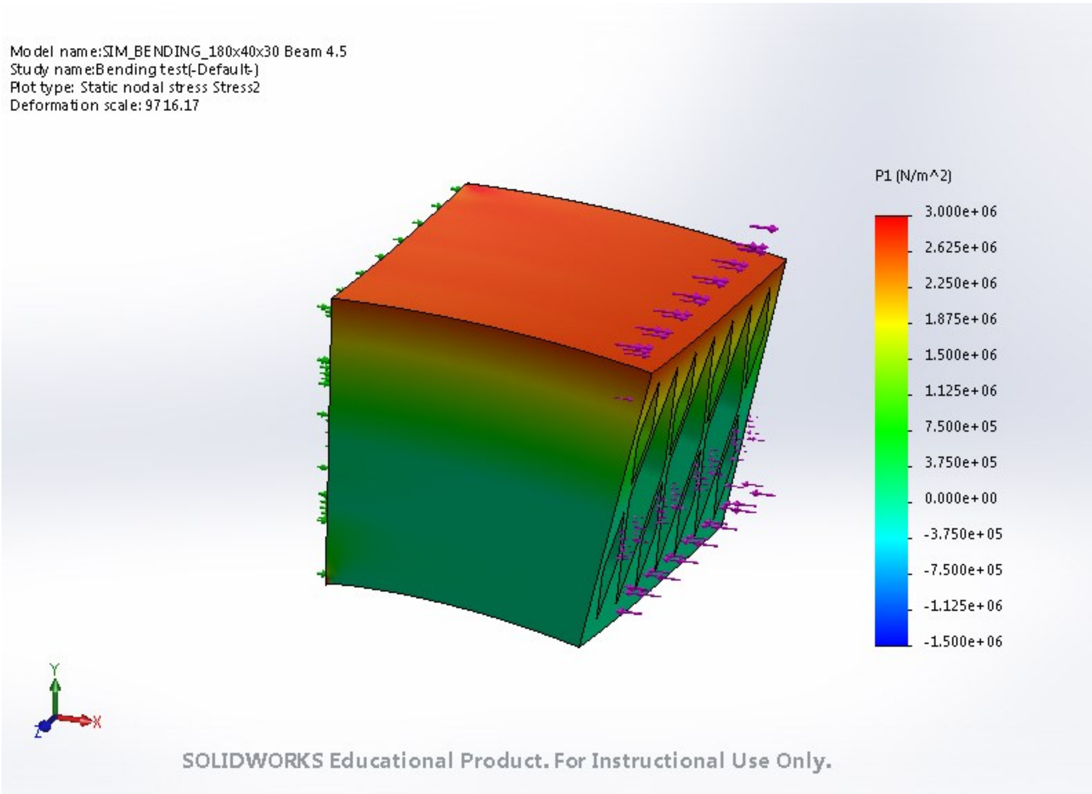


Figure 5.33: 4.5 Model 1st Principal Stress Result [SolidWorks]

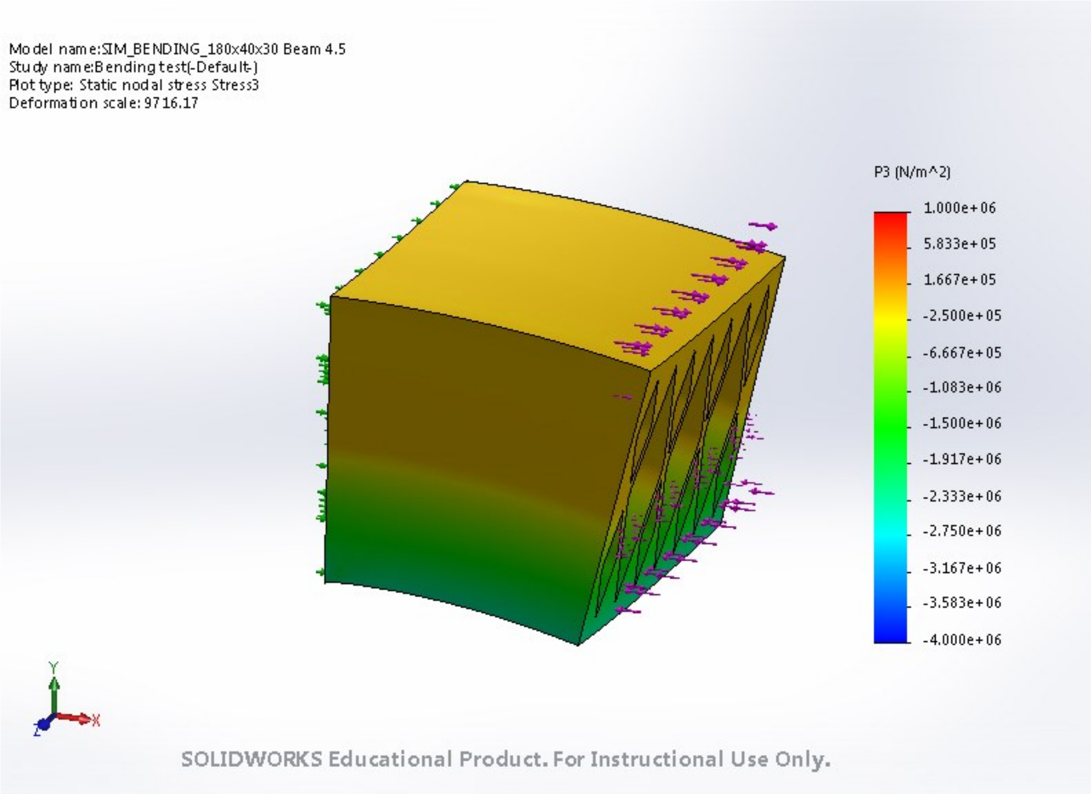


Figure 5.34: 4.5 Model 3rd Principal Stress Result [SolidWorks]

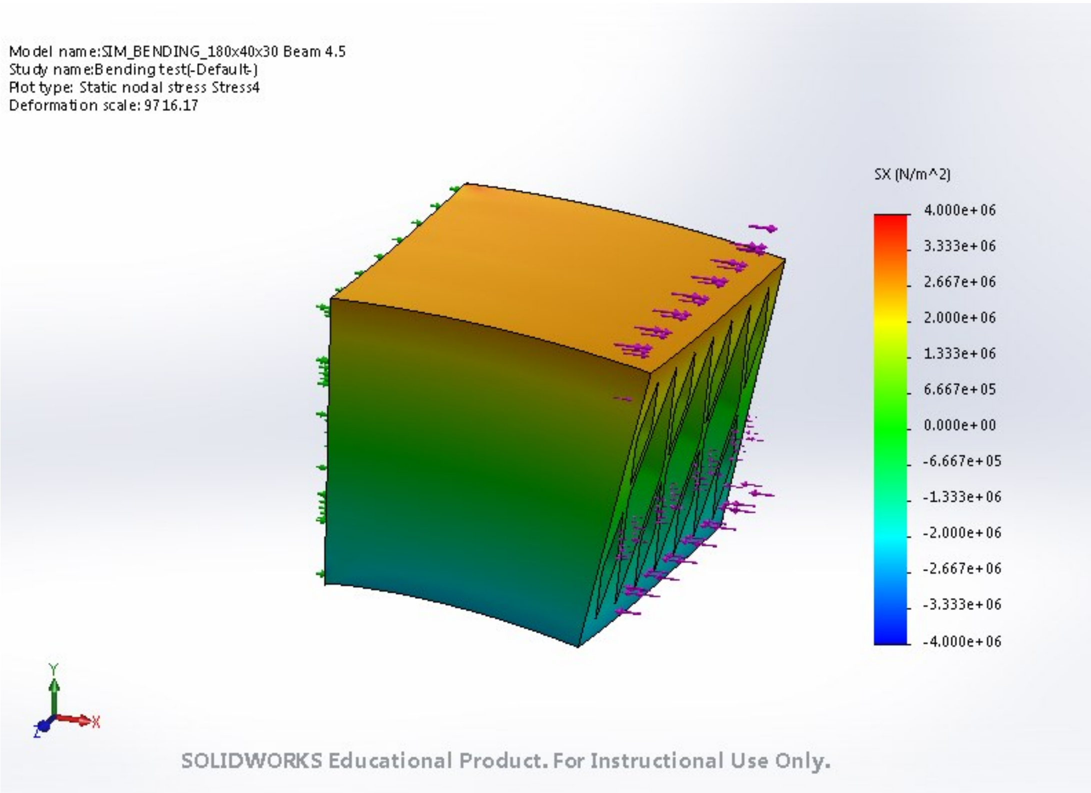


Figure 5.35: 4.5 Model X Normal Stress Result [SolidWorks]

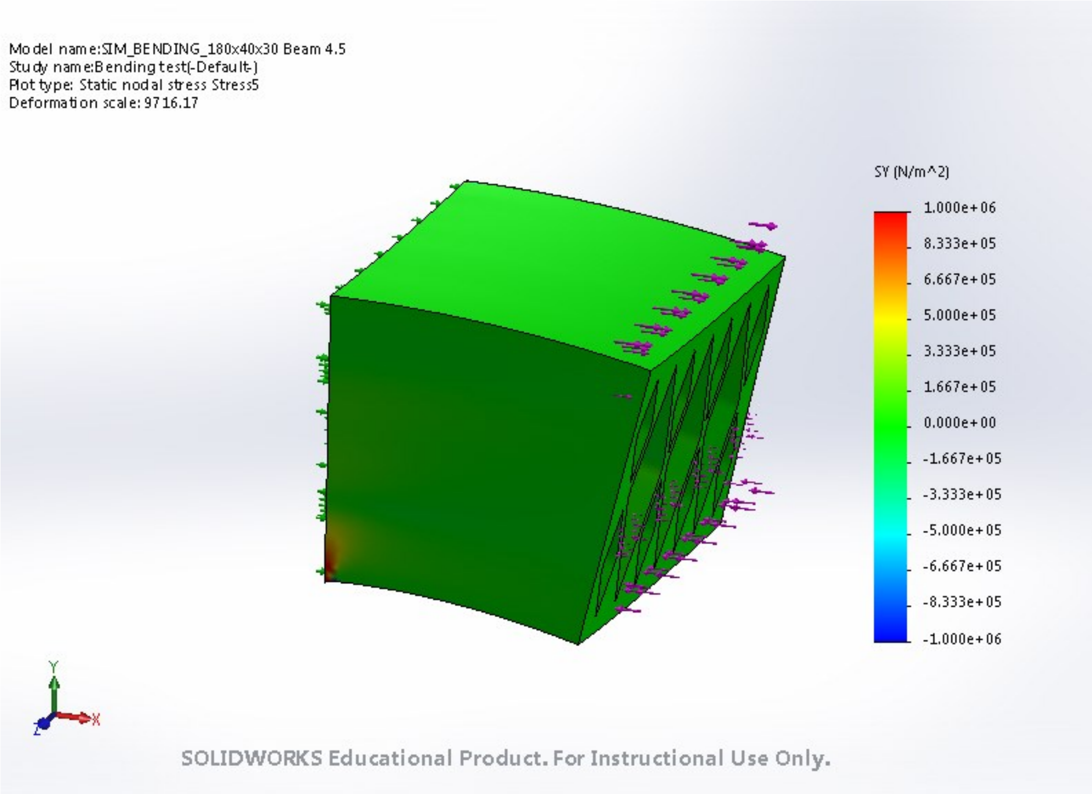


Figure 5.36: 4.5 Model Y Normal Result [SolidWorks]

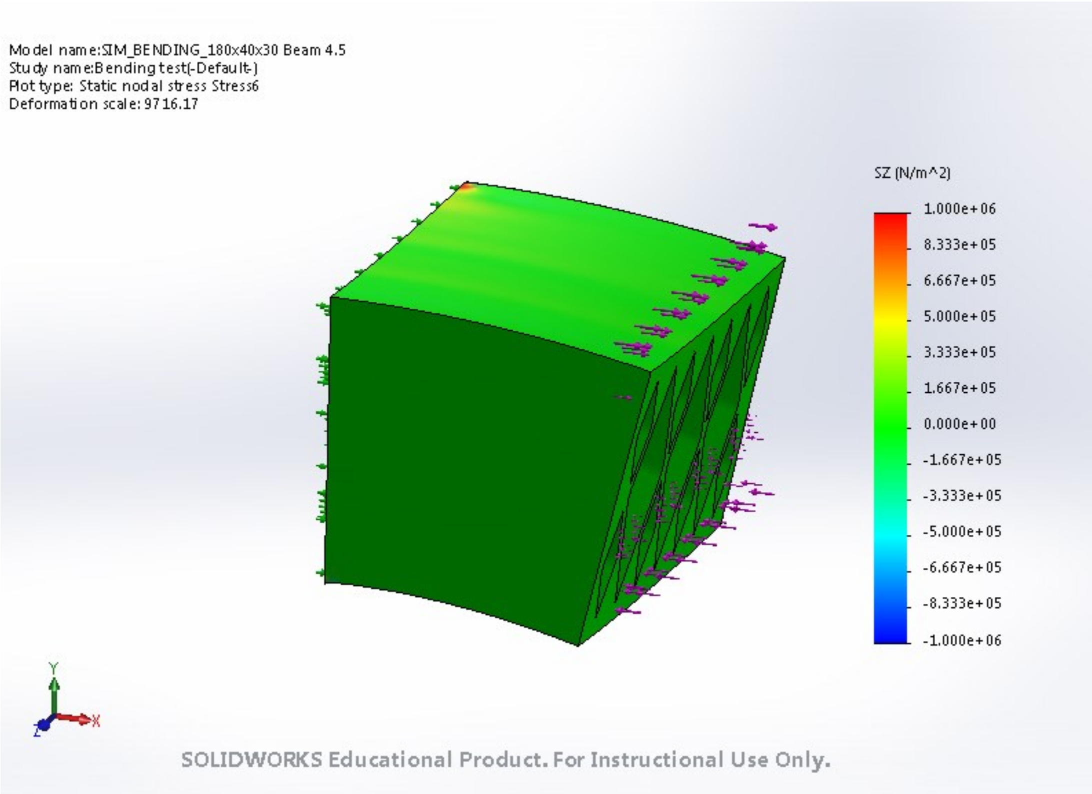


Figure 5.37: 4.5 Model Z Normal Result [SolidWorks]

5.1.2.3 Bending Test Simulation Beams Comparison

The following table, Table 5.1, is used to compare the beams 3.2.2 and 4.5 subjected to the same bending stress. It is possible to see that, obviously, the beam 4.5 has worse results than the 3.2.2 but it also reduces the area, which would be a great mass reduction in the case of a really long beam.

According to the simulations, it is possible to say that the both beams have the same qualitative result and the numerical results differ approximately a 7%.

There is no hidden result in these simulations because the beams are really similar. The beam 4.5 reduces the mass in the middle of the beam, achieving less total weight and only reducing a bit the moment of inertia.

Table 5.1: Simulation Results Summary [SolidWorks Simulation Report]

	Comments	Beam 3.2.2	Beam 4.5	Difference (%)
Displacement [mm]	Upper (Tension)	5.25E-04	5.61E-04	6.86%
Strain [kPa]	Upper (Tension)	1.02E-05	1.08E-05	5.88%
von Mises [kPa]	Upper (Tension)	2.55E+06	2.72E+06	6.67%
1st Principal [kPa]	Upper (Tension)	2.55E+06	2.73E+06	7.06%
	Bottom (Compression)	-	-	-
3rd Principal [kPa]	Upper (Tension)	-2.23E+06	-2.38E+06	6.73%
	Bottom (Compression)	-	-	-
SX [kPa]	Upper (Tension)	2.55E+06	2.73E+06	7.06%
	Bottom (Compression)	-2.23E+06	-2.39E+06	7.17%
SY [kPa]	Upper (Tension)	-	-	-
	Bottom (Compression)	-	-	-
SZ [kPa]	Upper (Tension)	-	-	-
	Bottom (Compression)	-	-	-
Area [mm^2]		661.97	611.53	-7.62%
Moment of Inertia (I_y) [mm^4]		689.30	674.30	-2.17%

5.2 Experiments

The images and graphs from the experiments done in the lab are shown next with its explanation and discussion.

5.2.1 Compression Test

The following figure, Figure 5.38, shows how the nine specimens ended after the compression test. It can be seen how specimens 1, 2 and 3, suffered a lot of buckling before failing. In the case of specimens 4, 5, 6, 7, 8 and 9, it was totally different, the buckling effect and compression load separated the layers, due to lower cohesion between layers build in that direction.

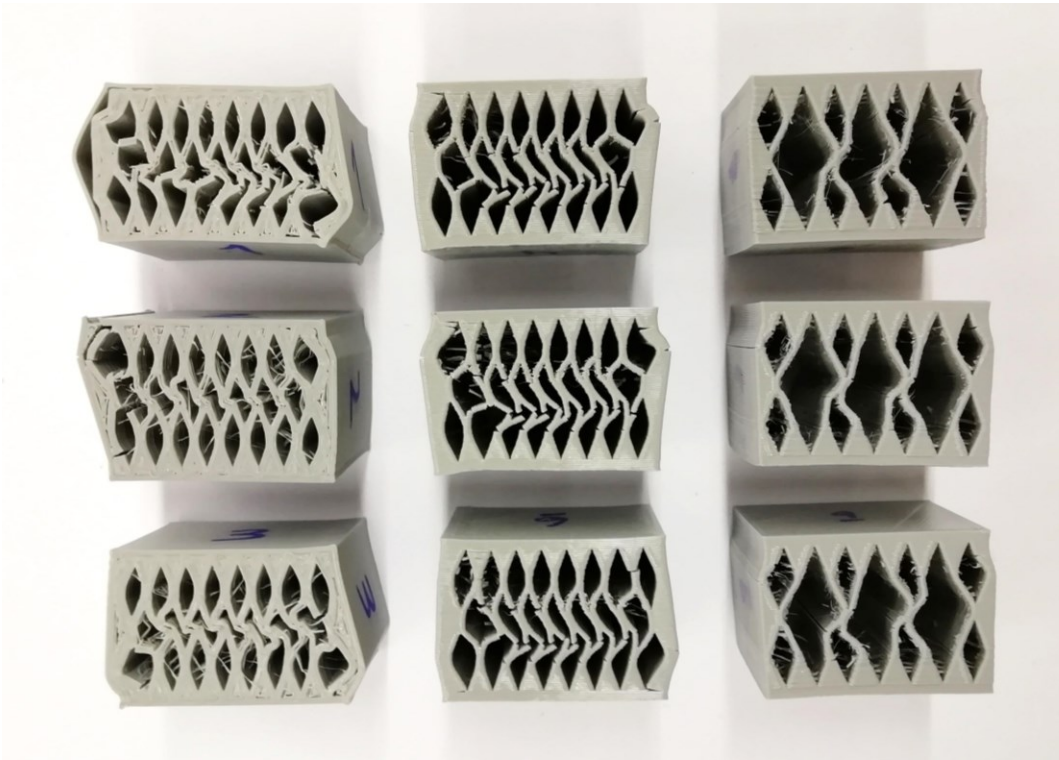


Figure 5.38: Compression Test Bricks after destructive test.
Column 1 for Bricks 3.2.2, specimens 1, 2, 3.
Column 2 for Bricks 3.2.2, specimens 4, 5, 6.
Column 3 for Bricks 4.5, specimens 7, 8, 9.

Remember that the filaments of specimens 1, 2 and 3 were placed in the Y and Z axis and that ones from specimens 4, 5, 6, 7, 8 and 9 were placed in the X axis, the same direction that was used for the beams.

The results obtained have very low variance so great repeatability. This is great to discuss and give supported conclusions.

5.2.1.1 Brick 3.3.2 printed in the X direction

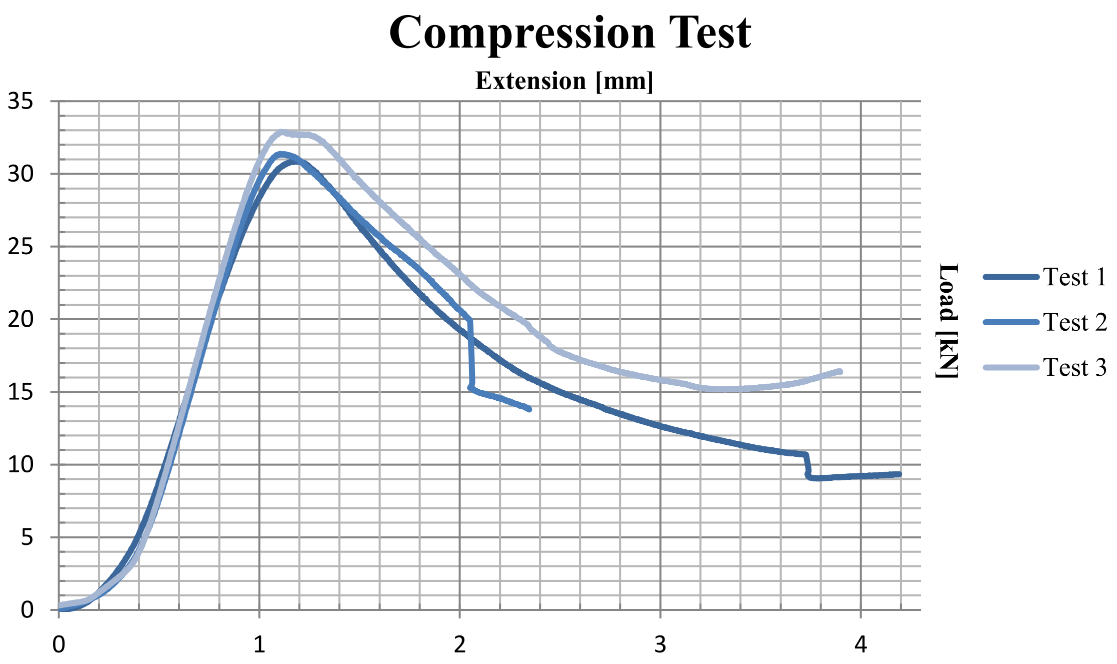


Figure 5.39: Compression Test Graphic for Specimens 1, 2, and 3.

5.2.1.2 Brick 3.3.2 printed in the Y direction

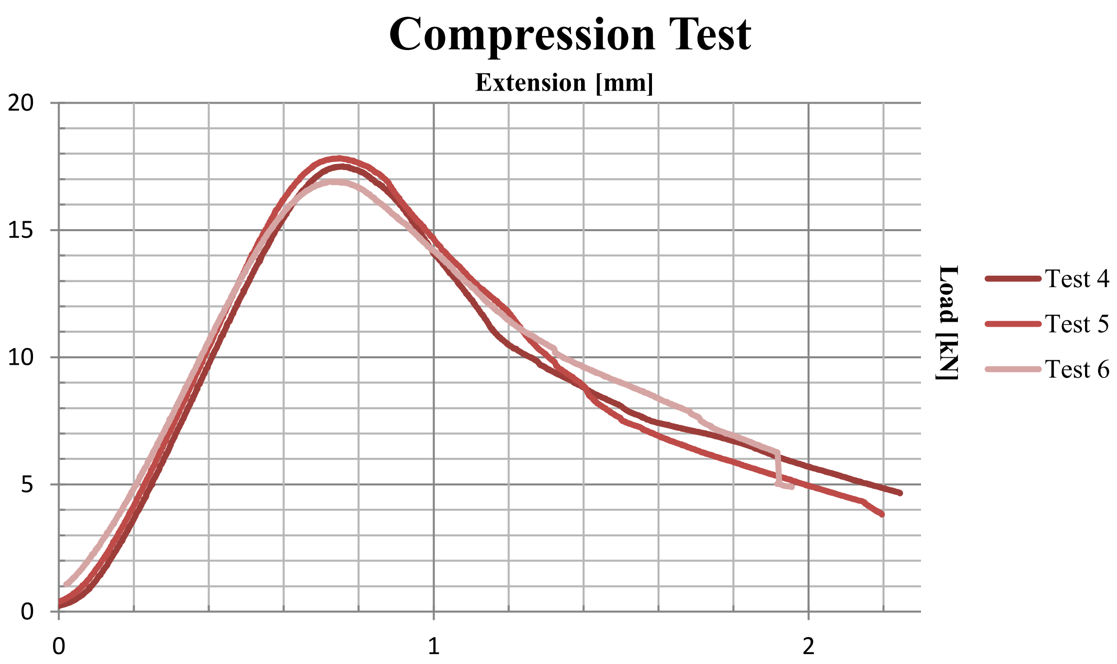


Figure 5.40: Compression Test Graphic for Specimens 4, 5, and 6.

5.2.1.3 Brick 4.5 printed in the Y direction

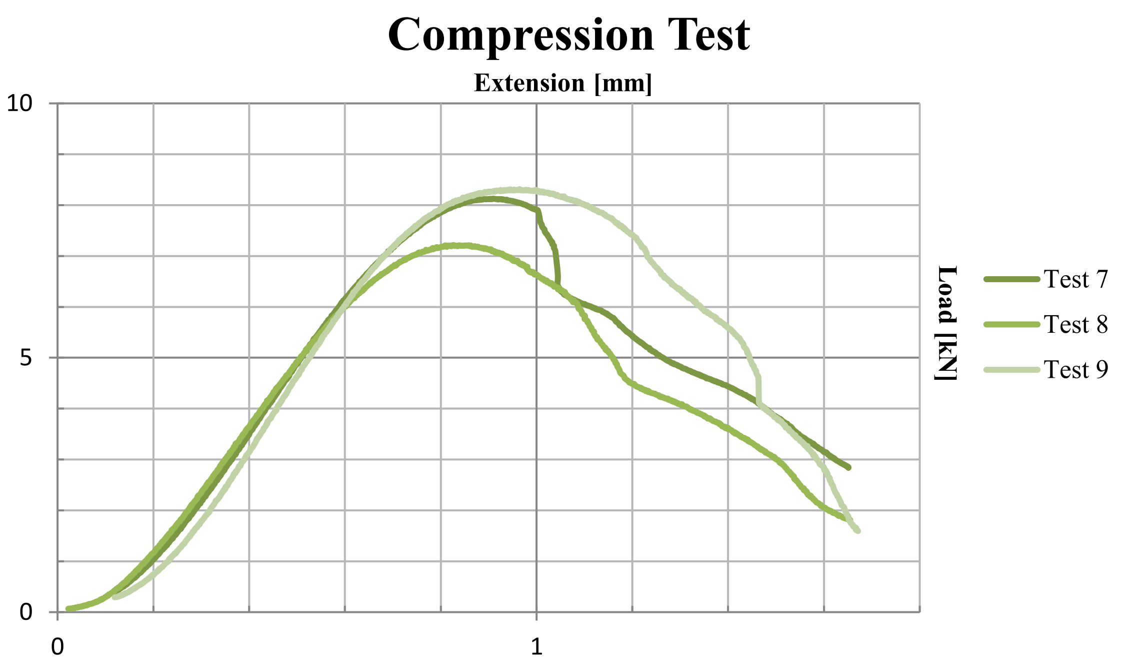


Figure 5.41: Compression Test Graphic for Specimens 7, 8, and 9.

5.2.1.4 Compression Test Bricks Comparison

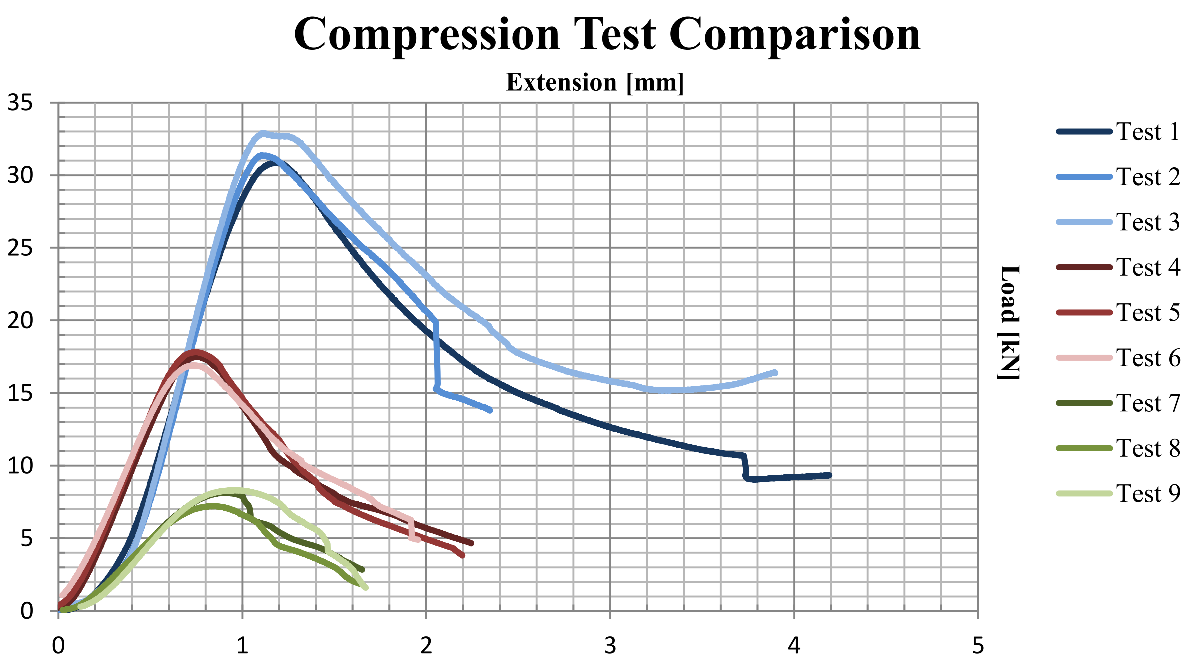


Figure 5.42: Compression Test Comparison Graphic between all Specimens.

Table 5.2: Maximum Load numerical results for Compression Bricks

Specimen	Load [kN]	Load Mean [kN]	Load Standard Deviation [kN]
1	30,861	31,697	1,055
2	31,374		
3	32,891		
4	17,508	17,411	0,145
5	17,827		
6	16,910		
7	8,127	7,870	0,232
8	7,213		
9	8,314		

After these experiments it is really easy to compare between building directions, X and Y axes, and the models, 3.2.2 and 4.5.

The specimens 1, 2 and 3 have obtained the best results because its filaments are mostly oriented or partially oriented in the direction of the pressing load. These are good results comparing to the specimens 4, 5 and 6, that its filaments are oriented in the most critical direction, 0º. This experiment is enough to show how anisotropy deeply affects AM technologies, in specific FDM technology. Building in the 0º, in this case, decreases the performance almost in half.

Finally, 3.2.2 model specimens, 4, 5 and 6, and 4.5 model specimens, 7, 8 and 9, are used to compare how these models perform subjected to compression. Although, it is already obvious that the 3.2.2 model would give better results, it is denser and have a more complete internal structure. However, it might not be expected that the model 4.5 would give these really bad results.

It may seem like when experimenting, 3.2.2 model brick is a lot better than expected, compared to 4.5 model brick.

5.2.2 Bending Test

The following figure, Figure 5.43, shows how the four specimens ended after the bending test. It can be seen that all of them started cracking in the point of application of the load, at the compression side, the crack moved its direction perpendicularly, probably due the lack of cohesion between the layers, and, finally, cracked again at the bottom, the tensile side.

The beams failed in a hard way, ending in pieces. All of them failed in a similar way and adding repeatability to the experiment.

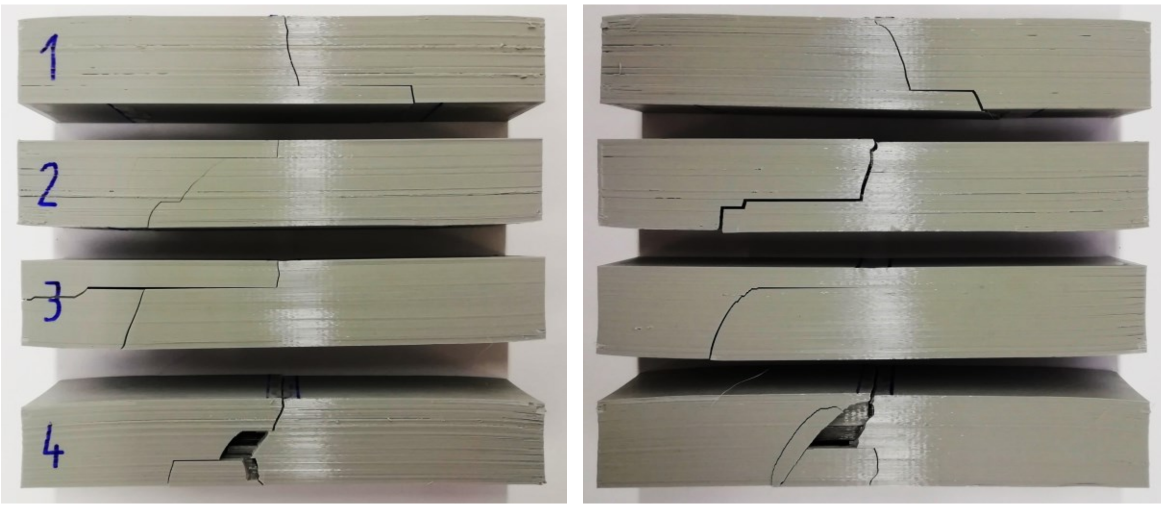


Figure 5.43 Bending Test Bricks after destructive test (Backside beams image mirrored)
Row 1 for Beam 4.5, specimen 1.
Row 2 for Beam 4.5, specimen 2.
Row 3 for Beam 3.2.2, specimen 3.
Row 4 for Beam 3.2.2, specimen 4.

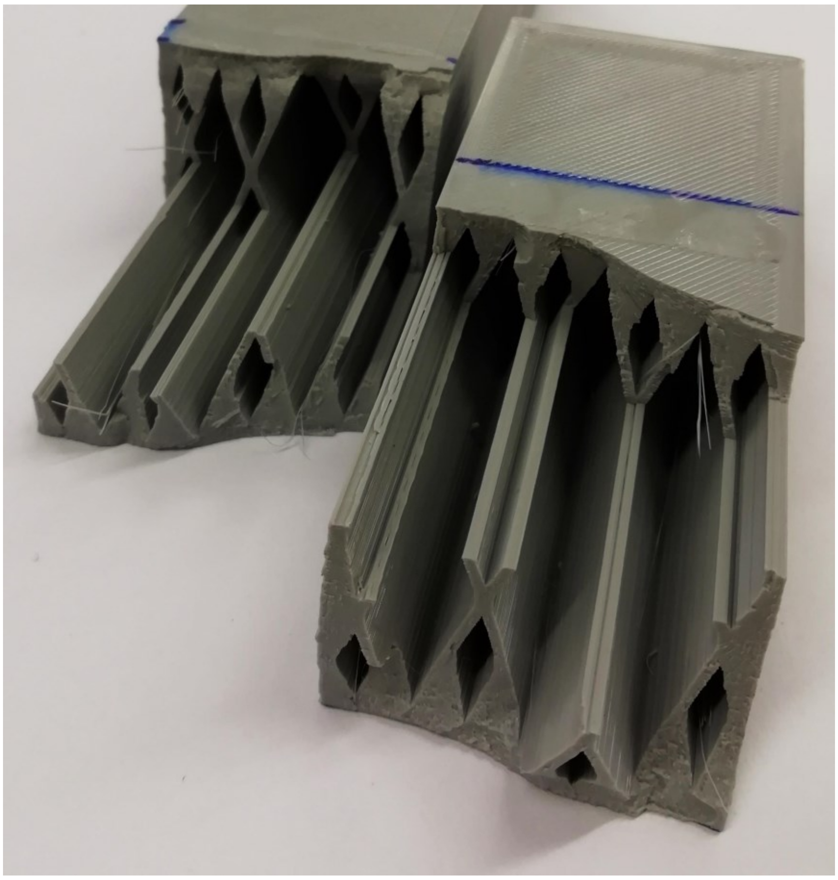


Figure 5.44: Specimen 1 after testing

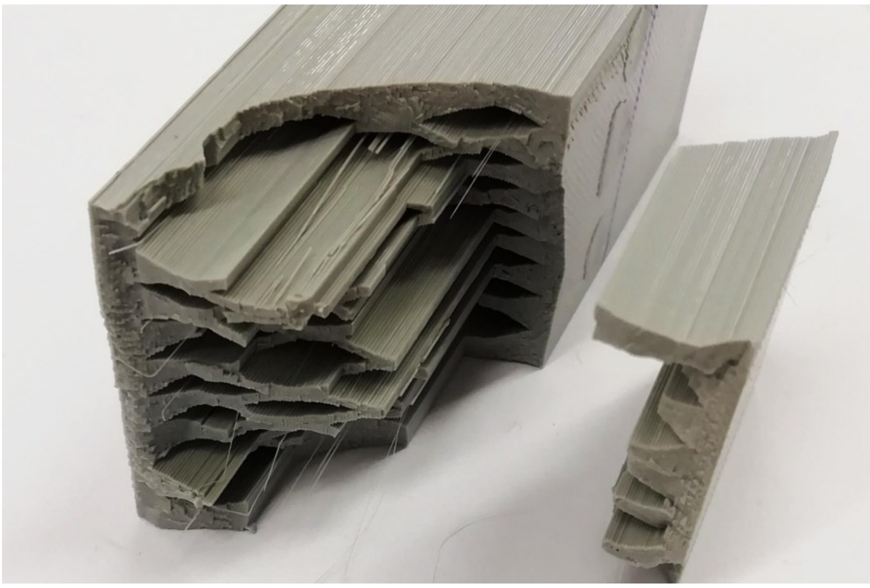


Figure 5.45: Specimen 4 after testing.

In Figure 5.44 and Figure 5.45, it is possible to see how the upper and lower parts failed because of compressive and tensile stress in the direction of the filament. On the other hand, in the middle, part of them failed because of separation between layers due to the shear stresses between the printed layers of filament. It happened in beams 4.5 and 3.2.2 so it is not only related to one of them.

In the following figures, Figure 5.46 and Figure 5.47, it is possible to appreciate how the filaments are placed in the X direction. The minimum filament width of the beam is three filaments. It also can be seen how some parts failed separating two layers of filaments.

There are two modes of failure: filaments breaking, related to compressive and tensile stress, and filaments or layers separation, related to shear stress.

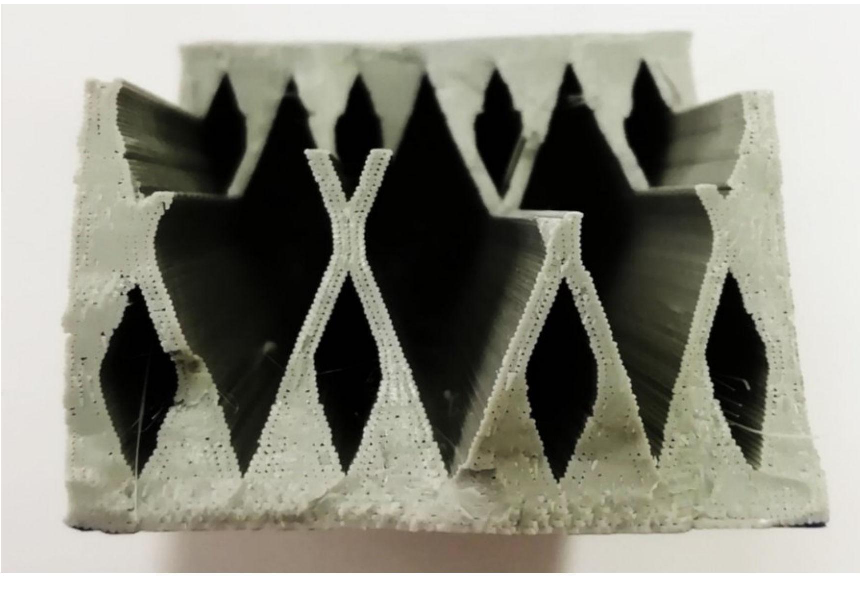


Figure 5.46: Specimen 1 after testing. Filament observation.

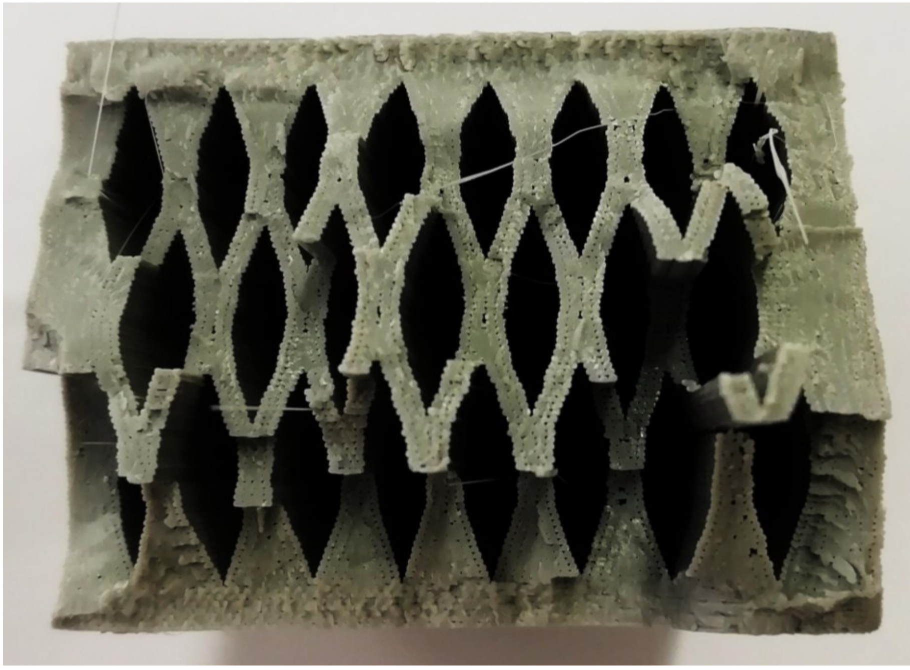


Figure 5.47: Specimen 4 after testing. Filament observation.

Note that, unluckily, it was not possible to record the data of specimen 2 bending test. However, seen the low variance and high repeatability experienced in the past and in this experiment, this thesis uses that single results as valid.

5.2.2.1 Beam 4.5

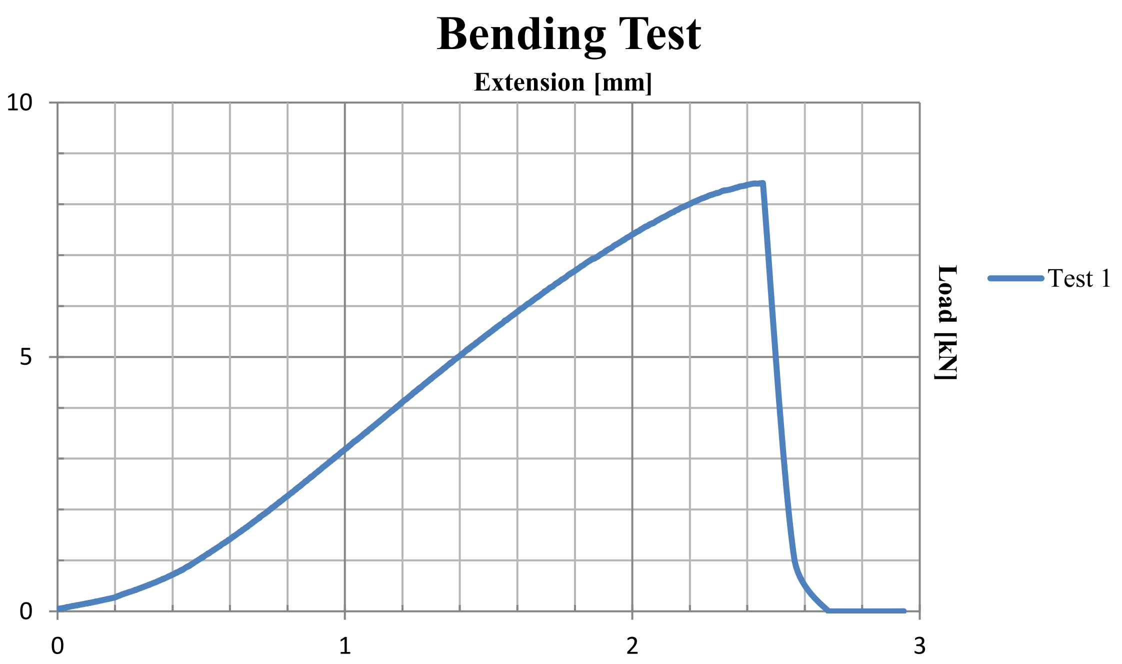


Figure 5.48: Bending Test Graphic for Specimen 1

5.2.2.2 Beam 3.2.2

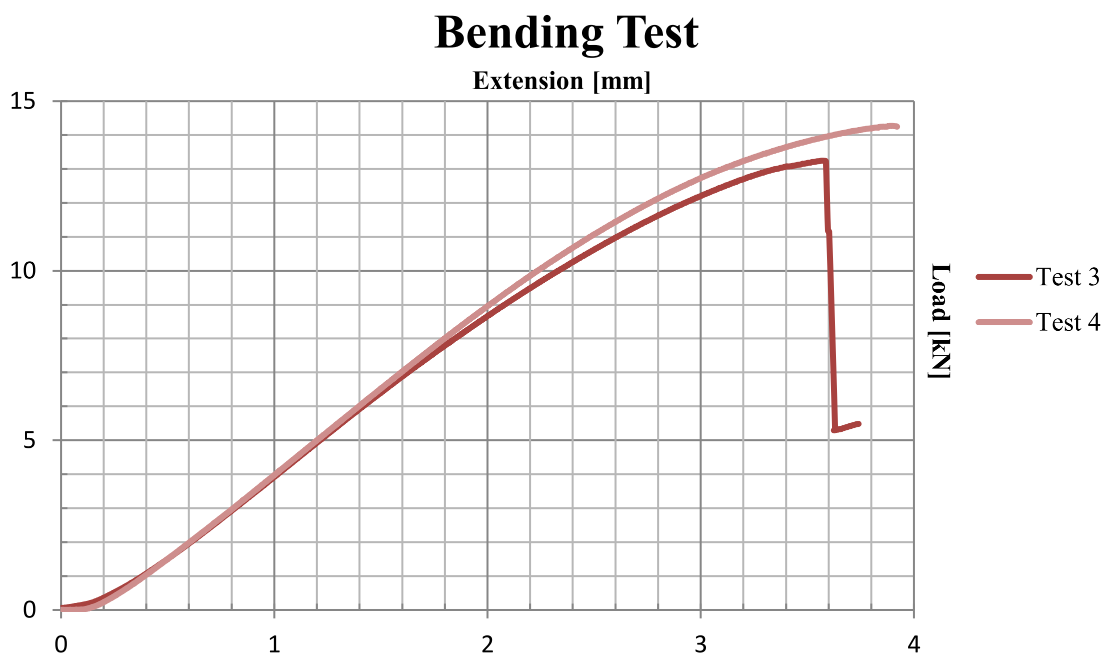


Figure 5.49: Bending Test Graphic for Specimens 3 and 4

5.2.2.3 Bending Test Beams Comparison

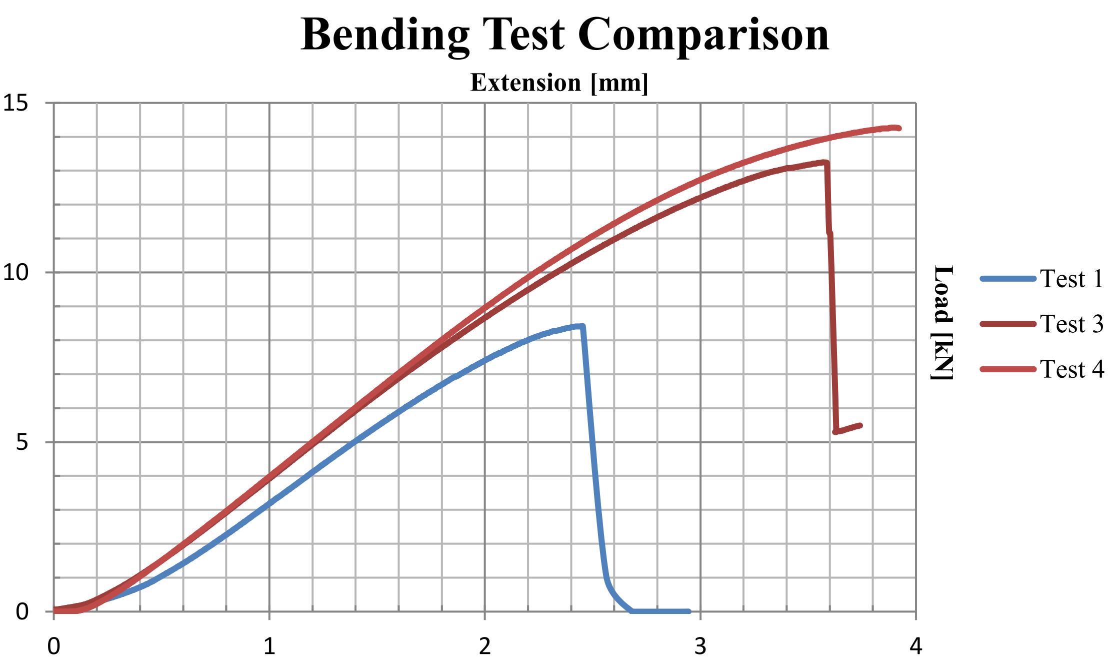


Figure 5.50: Bending Test Comparison Graphic for all Specimens

Table 5.3: Maximum Load numerical results for Bending Beams

Specimen	Load [kN]	Load Mean [kN]	Load Standard Deviation [kN]
1	8,416	8,416	-
2	-		
3	13,248	13,750	0,262
4	14,271		

As expected, the beam 4.5 obtained worse results than the beam 3.2.2. However, according to simulation the results should not differ that much. According to the experiments, the beam 4.5 is not as good as expected. It is lighter, has a similar moment of inertia and pretended to be and improvement of beam 3.3.2, reducing mass in the centre and keeping similar mechanic properties.

At the end, beam 4.5 was a lot worse than expected and this could be caused by different reasons. The most probable reason is that the design exceeded the technology limitations. This design should be tested with other technologies and other dimensions applying the same concept.

In the end, there was an extra bending experiment with a 4.5 beam. However, wanting to record the experiment with a high-speed camera to see how the beam would break, the beam could not be at ambient temperature anymore. The illumination needed for the high-speed camera increased the beam temperature reducing the properties of the thermoplastic material. It was considered that the results differed too much to be accepted.

This is why four tensile experiments, at high and ambient temperature, were added to the thesis, in order to measure the effect of temperature on the material and determine why the last high temperature 4.5 beam bending test experiment was not correct.

5.2.3 Tensile Test

In order to measure the effect high temperatures, 50ºC, on the mechanical properties of the material four tensile test were performed. Two of them, tests 8 and 9, were done at ambient temperature, considered to be 20ºC, and the other two, tests 11 and 12, at a higher temperature, 50ºC, caused by a light source.

In this case, stress and elongation was measured.

5.2.3.1 Ambient Temperature (20ºC)

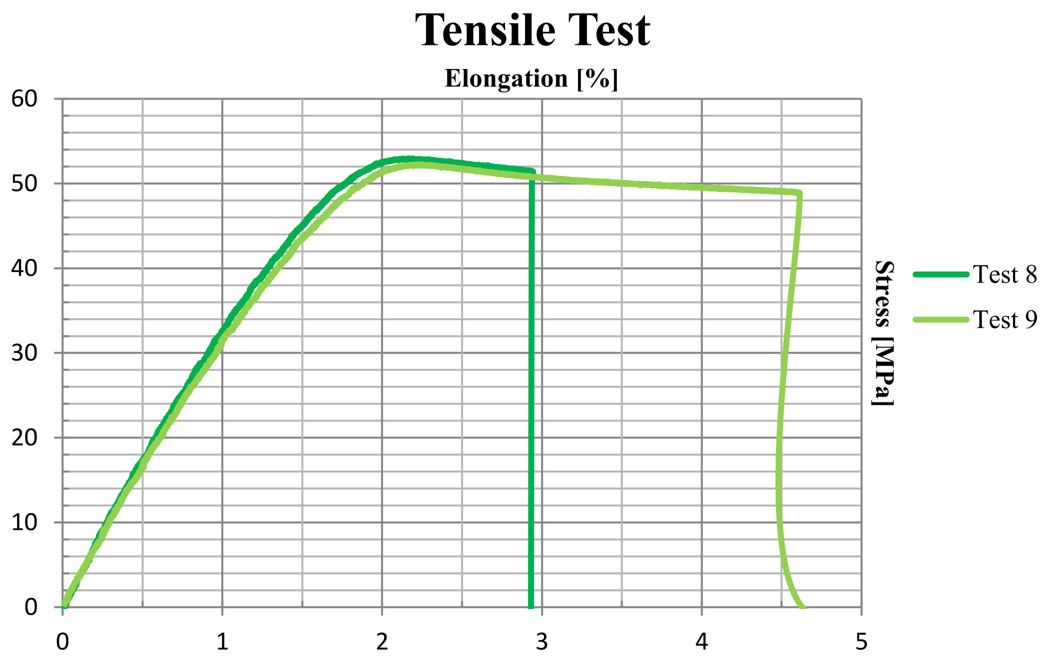


Figure 5.51: Tensile Test Graphic for Test 8 and 9

5.2.3.2 High Temperature caused by a light source (50ºC)

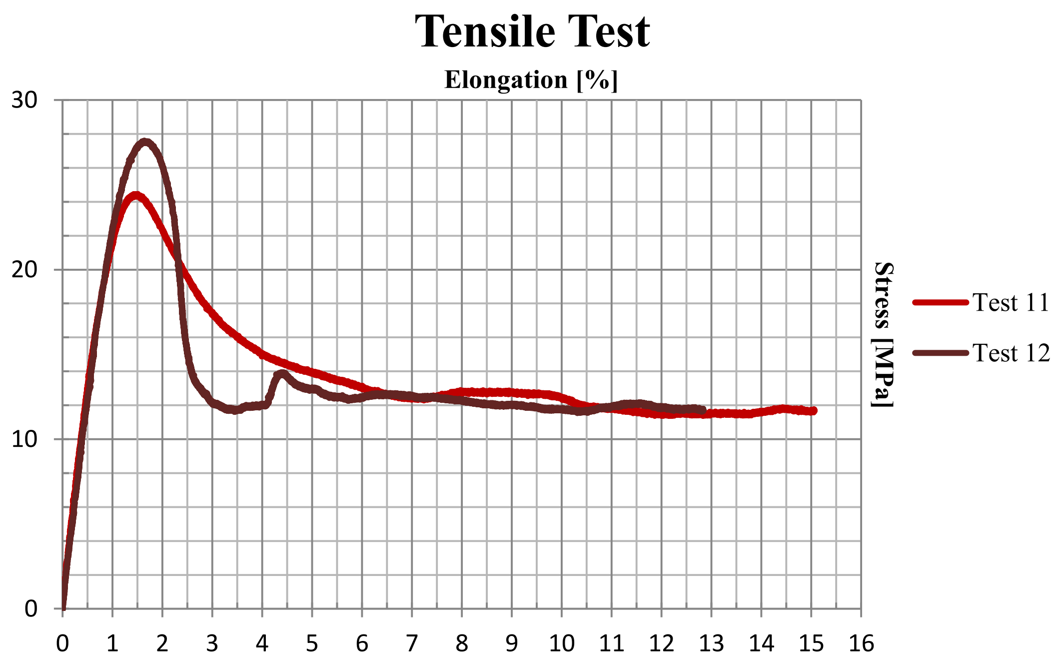


Figure 5.52: Tensile Test Graphic for Test 11 and 12

5.2.3.3 Tensile Tests Comparison

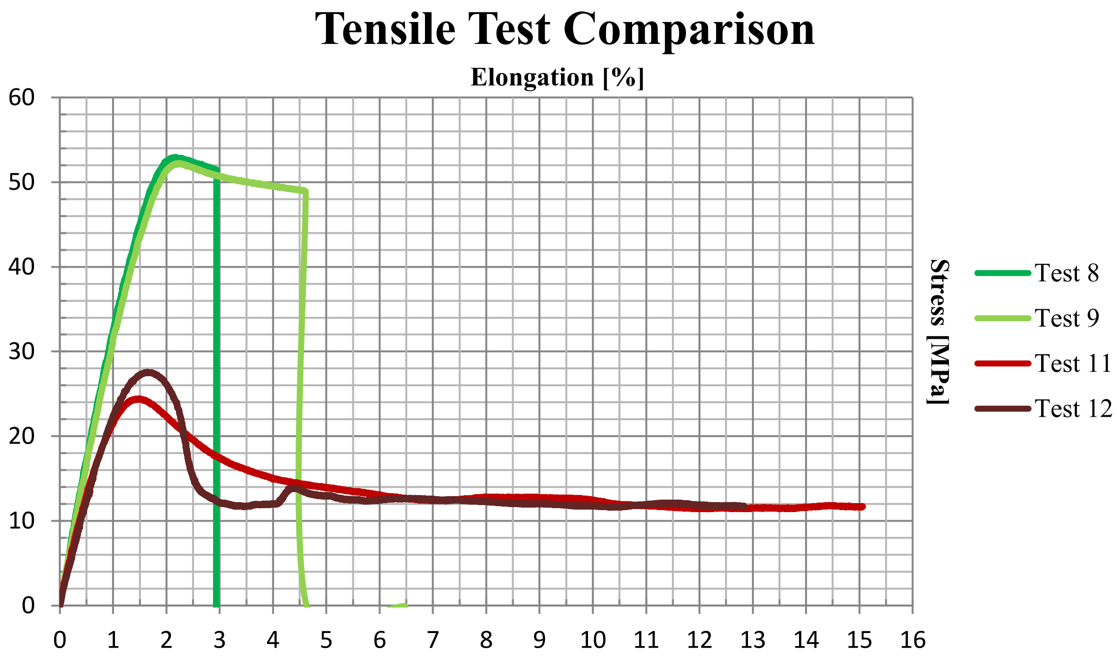


Figure 5.53: Tensile Test Comparison Graphic for all Specimens

It can be perfectly seen that the temperature has a big influence in the mechanical properties of PLA. It reduces drastically its maximum stress, reduces the elastic module and also change completely the maximum elongation.

In high temperatures, the material does not suddenly break hard. It keeps extending when applying a constant load, acting like a ductile material.

5.3 Correlation between simulations and results obtained by experiments

It is thought that is really hard to create an anisotropic finite element AM model that could predict how the real material will really work. There are a lot of parameters that may affect it and most of them hard to predict. Therefore, the results from simulations and experiments do not really correlate.

The simulations are useful to evaluate the design but not its real application because it is not possible to define a correct FE AM FDM model.

6 Conclusion

From the research work performed it can be concluded the following:

1) It was demonstrated that anisotropy is a really important parameter of Additive Manufacturing technologies parts. It allows some specific directions to have much better strength.
2) Building direction defines the strength of a part and it is as important as the design itself.
3) The results obtained show that if the technology limitations are exceeded the part does not perform as expected. It would perform worse than what it is expected from the design.
4) Due to very different mechanical properties between X axis and Y axis, the two failure modes are almost equivalent despite the fact that the shear stress near the neutral axis is much smaller that the shear strength of the basis material. However, with the manufacturing process applied it is the adhesion between the deposited layers that affects the rupture in the shear direction, not the shear strength of the material itself. This means that bending stress, compressive and tensile stress, and shear stress affect similarly the part.
5) Temperature has a big effect on PLA material and reduces drastically its mechanical properties.

The AM technology used may be restricting the design of the part wanted to produce, reducing drastically the part strength properties if the technology limitations are exceeded. In this case, it is considered that one of the specimens had worse results than expected because of this reason.

This thesis is very useful to understand how AM anisotropy works and see which are the parameters and details that need special attention when building an AM part. A method for producing AM semi-hollow bending beams was designed and tested, finding that anisotropy and technology limitations have a big influence on the results.

Finally, it is thought that the current method could be immediately used to build semi-hollow Powder Bed Fusion bending beams. It just needs to be slightly adapted to the technology parameters and limitations.

Thanks to this method, to design and produce semi-hollow parts, created it is possible to build parts that would be impossible to build without removable supporting structures. Using the current method, the parts are stronger and there is no need to remove the supporting structures.

Recommendations for future research

The use of AM technologies for real applications in the industry is not a new thing anymore. Moreover, it is a great technology to build prototypes and small lot parts. Its limitations and possibilities should be investigated carefully to achieve the use its full potential.

It would be recommended to test the current method with different technologies, finding the technology limitations and how they affect the design.

The current method could be adapted to any other technology changing the dimensions of the pattern making the structure more or less dense. Moreover, the overhanging angles could be wider if the technology allows it, allowing the internal structure to have wider holes. The width of the internal links could also be reduced or increased according to the technology and necessities.

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